MS No.: egusphere-2026-973:
Answers to the Editor and Referees

Original Referee comments are in italics, **authors' response is in bold**.
All revisions described in this response have been fully implemented in the clean revised manuscript, and all line-number references correspond exclusively to the clean revised manuscript.

Authors' response: We thank the Editor and the anonymous Referees for their time and efforts in reviewing our work and providing insightful comments. We have now addressed their comments and provided a point-by-point response to their comments in this document. We believe our manuscript has an improved focus and clarity after implementing the valuable suggestions from the Referees. On behalf of my co-authors, we would like to thank you for the time and effort in considering this manuscript.

Referee #3: Anonymous

Major comments:

The mHM model use temperature-based ET and snow accumulation and melt modeling approaches. I would say this is acceptable for the historical evaluations, given that calibration was performed using historical climate data. However, because these critical processes are oversimplified and may be predominantly sensitive to temperature rather than to other meteorological forcing variables, such as humidity, longwave radiation, shortwave radiation, and wind speed, this type of process parameterization could be questionable for future periods,when climate conditions may be outside the historical range. In other words, there is no guarantee that the calibrated parameters will remain optimal, and ET and snow dynamics may be sensitive to changes in other climate variables in the future. In the discussion, there are brief comments on this PET limitations, but I would suggest expanding this discussion to explain why the current PET formulation, and possibly the snow model, have potential limitations for analyses involving climate change.

Authors' response #1: We thank the Reviewer for the comment. We agree that the temperature-based PET formulation and the degree-day snow routine represent simplified process descriptions, particularly when applying the model under future climate conditions. We have therefore expanded the discussion to make this limitation more explicit. The Hargreaves-Samani formulation was used here mainly for consistency with the existing continental mHM setup and because the present study relies on precipitation and temperature forcing from EOBS and ISIMIP2b. This choice provides a consistent modelling chain for historical and future scenarios. However, it does not explicitly account for changes in humidity, radiation, wind speed, or atmospheric CO_2, which can influ-

ence evaporative demand under climate change. Similarly, the degree-day snow module captures the dominant temperature control on snow accumulation and melt, but it does not explicitly represent all energy-balance controls on snowmelt, such as radiation, turbulent fluxes, albedo changes, or rain-on-snow processes.

At the same time, the main target variable in this study is runoff drought rather than actual evapotranspiration itself. Previous mHM-based PET sensitivity analyses over European catchments showed that PET method choice can substantially affect PET and AET trends, but that runoff trends are generally less sensitive to PET formulation than AET, particularly in energy-limited and mixed catchments, where precipitation changes tend to dominate runoff variability (1). This supports the use of the current setup for assessing broad runoff-drought changes, while caution is still required when interpreting drought mechanisms involving enhanced evaporative demand or snow-process changes. We have therefore revised the Discussion to clarify that the projected changes should be interpreted as conditional on the selected PET and snow formulations. In particular, the robust signals for rainfall-deficit and wet-to-dry droughts are mainly interpreted in relation to precipitation and seasonal water-balance changes, whereas temperature-dependent drought types, especially rain-to-snow and snow-related categories, are discussed more cautiously because their magnitude and timing may be affected by the simplified PET and snow parameterizations.

Even though the GCM data are bias corrected, the reference meteorological data used for GCM bias correction are not EOBS data (please clarify this). Different observed or reference datasets may have systematic differences among them. Therefore, even though mHM works well with EOBS, simulations forced by the reference meteorological dataset used for GCM bias correction, as well as by bias-corrected GCM data, may produce systematic differences relative to mHM simulations forced by EOBS. The question is: how different are temperature and precipitation from the bias-corrected GCMs from EOBS during the historical period? If there are systematic differences, how do these forcing differences affect hydrologic fluxes, states, and drought detection? Do these forcing differences contribute to the underestimation of drought events presented in Section 3.1?

Authors' response #2: We thank the reviewer for raising this important point. We agree that the reference meteorological dataset used for the bias correction of the GCM simulations differs from EOBS, and that systematic differences among observational and reference datasets may propagate into hydrological simulations. However, in the present study, the EOBS-driven mHM simulations were primarily used to establish a first-order benchmark of drought characteristics against which the droughts simulated by the bias-corrected climate model ensemble could be evaluated. We note that, despite the differences in the underlying meteorological datasets, the resulting drought characteristics show a reasonable level of agreement. After establishing this step, the entire analysis of past and future changes in drought categories was conducted consistently using the climate model-based simulations.

Nevertheless, we acknowledge that differences between E-OBS and the

reference dataset used for GCM bias correction may influence the simulated hydrological fluxes, states, and consequently drought detection. To better address this concern, we will include an additional analysis in the revised manuscript comparing the historical precipitation and temperature fields from EOBS with those the reference dataset used in the GCM bias-correction procedure. This comparison will help identify any systematic differences in the meteorological forcing and provide additional context for interpreting differences in simulated drought characteristics.

I wonder whether the CMIP5 GCM forcing is the mean of ensemble members or is taken from a particular ensemble member for each GCM. Note that this is not the same use of the term "ensemble" as in the paper: each CMIP GCM run may have several different historical-future traces based on GCM initial conditions, in addition to different emission scenarios. I do not think this was mentioned in Section 2.1. I doubt that the GCM forcing is an ensemble-member mean, but I wanted to check. If it is an ensemble-member mean, extremes would be reduced, which could contribute to fewer drought detections (or less severity). Also, since drought detection was percentile based, how is the percentile at each location computed? Is it computed separately for each forcing dataset at each location?

Authors' response #3: We will add the definition of the ensemble mean to the manuscript. In this study, the ensemble mean represents the average of the outputs from the five GCM models. We will also clarify the percentile threshold calculation method by stating that each variable was standardized relative to the 1971–2000 reference period, and the percentile threshold (τ) used for drought identification was calculated from the corresponding normalized historical baseline. The same historical threshold was applied to both historical and future periods for event identification. This fixed historical-threshold approach was used to quantify changes in drought characteristics relative to historical climatological conditions.

Minor comments:

L45: Please explain what "warm" and "cold" snow mean. I guess "season" is missing? I would suggest explaining these terms here, rather than only referencing past papers.

Authors' response #1: We thank the reviewer for this helpful suggestion. We agree that the terms "cold-snow-season drought", "warm-snow-season drought", and "snowmelt drought" should be explained when first introduced. We have therefore added definitions in the Introduction at lines 49–53 of the revised manuscript. Specifically, we now clarify that cold-snow-season droughts refer to runoff deficits during periods when sub-zero temperatures allow precipitation to accumulate and remain stored as snow, thereby delaying runoff generation; warm-snow-season droughts refer to runoff deficits during relatively warm snow-season conditions, when snow accumulation is limited or existing snow storage is depleted earlier than usual; and snowmelt droughts occur when reduced or earlier-depleted snow water equivalent limits runoff during the melt season.

L58-59: Regarding the rain-to-snow mechanism: From the explanation in parentheses, I understand that this refers to a deficit of snowfall, leading to low snow accumulation and affecting spring-summer water availability. Is this interpretation correct? Or does this have something to do with the snow to rain transition due to weather patterns in specific years and/or climate change? The term "rain-to-snow" does not seem to match the explanation in parentheses. Reading further down, there are also snow-related processes. From this part of the paragraph, it is unclear how the rain-to-snow and snow-related processes are different.

Authors' response #2: We thank the reviewer for this helpful comment. We agree that the term "rain-to-snow" could be misunderstood as a transition from snowfall to rainfall due to climate change or specific weather patterns. In this study, however, rain-to-snow drought refers to a drought mechanism in which a rainfall deficit continues into the snow season after temperatures fall below 0°C, rather than a change in precipitation phase. We have revised the description of the drought mechanisms in the Introduction to clarify this definition and to better distinguish rain-to-snow droughts from snow-related drought processes. The latter include cold-snow-season, warm-snow-season, and snowmelt droughts, which are associated with anomalies in snow accumulation, storage, and melt conditions. These clarifications have been added at lines 47–53 and lines 65–69 of the revised manuscript.
Original statement L58–59: Specifically, we examine how distinct mechanisms – rainfall deficits, rain-to-snow (rainfall deficits that continue into the snow season once temperatures fall below 0 °C),
Updated statement L65–69: Specifically, we examine how distinct mechanisms – rainfall deficits, rain-to-snow (rainfall deficits that continue into the snow season once temperatures fall below 0 °C), and wet-to-dry transitions (wet-season precipitation deficits that persist into the dry and high-evaporative-demand season), and snow-related processes (including cold/warm snow-season and composite types associated with anomalous snow accumulation and melt conditions) – respond to changes in climate.

Section 2.4 explain the drought types in detail. But I still suggest revising short description on drought types in the introduction. It might be helpful to include the paper outline in the end of introduction, so the readers expect the details of drought types in later section.

Authors' response #3: Yes, We agree that the Introduction should provide a clearer overview of the drought-type framework and guide readers toward the detailed methodology. The short description of drought mechanisms has been revised in the Introduction, while the full definitions and identification criteria remain in Section 2.4. We have also added a brief outline of the paper structure at the end of the Introduction to improve the organization and readability of the manuscript.

Added Sentence L81–84: The remainder of this paper is organized as follows. Section 2 describes the data sources, hydrological modelling framework, drought-event classification, and statistical analysis methods. Section 3 presents the historical evaluation of model performance, projected changes in drought characteristics, and spatial hotspot patterns. Section 4 discusses the implications, limitations, and transferability of the framework, and Section 5 summarizes the main conclusions.

L65: GCM is General Circulation Model or Global Climate Model.

Authors' response #4: We thank the reviewer for this comment. We have revised the manuscript to define the abbreviation at its first occurrence. The term "General Circulation Model (GCM)" is now introduced at line 72, and the abbreviation GCM is used thereafter.

Figure 2: It is a little strange to see a few white boxes that do not have a split. My understanding is that a white box represents a decision-node-like step, so it should have a split. Basically, is the box labeled "Transition to dry period" is description of "a wet to a dry season"? The same question applies to the warm snow season. For a decision tree like this, I would suggest removing these white boxes and characterizing the drought type, or terminal node, somewhere in the text.

Authors' response #5: The decision tree in Figure 2 follows the drought-process classification framework introduced by (2). The white boxes represent intermediate classification steps and diagnostic criteria used to separate different drought-generation mechanisms, rather than additional drought categories. The final drought types are shown as the terminal nodes (blue boxes). We agree that the original figure could be interpreted differently and have revised the labels and formatting of the intermediate steps to make their role in the classification procedure clearer. The detailed definitions of the resulting drought types are provided in Section 2.4.

Section 3.1: I suggest adding the total number of drought events and the bias for the GCM based results.

Authors' response #6: Yes, We agreed. We have added a quantitative comparison of historical GCM-driven drought events against the EOBS reference in Section 3.1. Table 3 now reports the total number of drought events, event fractions, and relative event-count biases for each GCM and the ensemble mean across drought types. The historical GCM simulations reproduce the dominant drought-event types identified from EOBS, with rainfall-deficit droughts representing the largest fraction of detected events. However, most models underestimate the total number of drought events relative to EOBS, with the relative biases varying among drought types and models Table 3 (refer to Table R1).

L211: It appears to me that wet-to-dry drought has the lowest biases overall, not rain-to-snow drought.

Authors' response #7: We have addressed this comment by adding the following sentences to the revised manuscript.
Updated statement Lines 254–258: Wet-to-dry droughts show the lowest relative bias among the drought typologies in the ensemble mean (-16.1%), indicating that this transition mechanism is better reproduced by the GCM simulations. Rain-to-snow droughts also show relatively small ensemble mean bias (-24.0%) but exhibit larger inter-model variability. In contrast, snow-related droughts, particularly snowmelt and composite droughts, are more strongly underestimated, with ensemble mean biases of -48.8% and -63.4%, respectively.

Table R1: Comparison of drought events between GCMs (RCP4.5) and EOBS (1971–2000), categorised by drought event type. *Number of events* refers to absolute counts in EOBS (N_{OBS}) or historical GCM simulations (N_{hist}). *Fraction of events* (%) indicates the proportion of each drought event type relative to the total event count per dataset. *Relative bias* (%) is calculated as $(N_{\text{hist}} - N_{\text{OBS}})/N_{\text{OBS}} \times 100$, representing the percentage difference between modelled and observed event counts. Negative values indicate underestimation by the model. The ensemble mean was calculated across the five GCMs.

Metrics	**Rainfall deficit**	**Rain to snow**	**Wet to dry**	**Warm snow**	**Cold snow**	**Snowmelt**	**Composite**
EOBS v25 observations							
Number of events	30993	3400	5273	957	2793	3952	475
Fraction of events (%)	64.7	7.1	11.0	2.0	5.8	8.2	0.9
MIROC							
Number of events	22222	2623	5243	682	1914	2110	121
Fraction of events (%)	63.6	7.5	15.0	2.0	5.4	6.4	0.3
Relative bias (%)	-28.3	-22.8	-0.6	-28.7	-31.5	-46.6	-74.6
GFDL							
Number of events	19842	3394	4414	476	1384	1725	85
Fraction of events (%)	63.4	10.8	14.1	1.5	4.4	5.5	0.3
Relative bias (%)	-36.0	-0.2	-16.3	-50.3	-50.4	-56.4	-82.1
HadGEM2							
Number of events	20992	2740	4681	561	2060	1952	96
Fraction of events (%)	63.5	8.3	14.1	1.7	6.2	5.9	0.3
Relative bias (%)	-32.3	-19.4	-11.2	-41.4	-26.2	-50.6	-79.8
IPSL							
Number of events	22502	2395	3848	572	1532	2663	251
Fraction of events (%)	66.6	7.1	11.4	1.7	4.5	7.9	0.7
Relative bias (%)	-27.4	-29.6	-27.1	-40.3	-45.1	-32.7	-47.2
NorESM							
Number of events	22412	1762	3933	458	1490	1674	316
Fraction of events (%)	69.9	5.5	12.3	1.4	4.6	5.2	0.9
Relative bias (%)	-27.7	-48.2	-25.4	-52.1	-46.7	-57.6	-33.5
Ensemble mean							
Number of events	21594	2583	4424	550	1676	2025	174
Fraction of events (%)	65.4	7.8	13.4	1.7	5.1	6.1	0.5
Relative bias (%)	−30.3	−24.0	−16.1	−42.5	−40.0	−48.8	−63.4

L224: Please specify what is meant by temperature-dependent drought. Does this include all types except rainfall-deficit drought?

Authors' response #8: The following lines were modified.

Original statement: Regional analysis shows pronounced negative biases for temperature-dependent drought event types in NEU and WCE (median -6 to $-8\,\mathrm{mm\,day^{-1}}$),...

Modified statement: Regional analysis shows pronounced negative biases for temperature-dependent drought event types (warm-snow-season, cold-snow-season, and snowmelt-related droughts)in NEU and WCE (median -6 to $-8\,\mathrm{mm\,day^{-1}}$),..

L252: Here, the temperature-dependent droughts are specified. I would suggest describing this in Section 2.4.

Authors' response #9: Thanks, We have revised in the previous comment.

L317-318: This sentence, stating that timing is stable, somewhat contradicts the statement that duration is generally longer. To me, there are some shifts in the starting and ending dates, with earlier starts and later endings; for example, WCE-rainfall. This overall statement does not seem to be accurate.

Authors' response #10: We thank the reviewer for this helpful suggestion. The following statement has been revised accordingly in the manuscript:

Original statement L317-318: Overall, the temporal analysis suggests that the seasonal timing of European droughts remains stable under climate change, but with longer durations and higher intensities.

Modified statement L378-383: Overall, the temporal analysis indicates that the seasonal occurrence patterns of European drought events remain broadly consistent under future climate conditions. However, the change analysis reveals regional- and drought-type-dependent shifts in mean drought onset and termination timing, with the strongest responses occurring for temperature-sensitive snow-related droughts. These timing changes, together with projected increases in drought duration and intensity, indicate a tendency toward longer drought persistence under future climate condition.

L379-380: Could this framework be used with other hydrologic or land-surface model outputs, in addition to its ability to examine other climate forcings? If so, explicitly mentioning this would promote the usability of this framework by allowing users to examine uncertainty arising from hydrologic model choices.

Authors' response #11: We thank the reviewer for this valuable suggestion. We have clarified that the framework can be applied to other hydrological and land-surface model outputs, allowing assessment of uncertainties associated with different model structures and process representations.

Modified statements L441-448: While the focus on RCP4.5 provides a plausible mid-range climate-change pathway, the projected changes should be interpreted as a CMIP5/ISIMIP2b case study based on five GCMs rather than as a full exploration of scenario and model uncertainty. Lower- or higher-emission pathways could alter both the magnitude and spatial extent of drought-type changes, and more severe forcing scenarios may lead to nonlinear hydrological responses not captured by the present ensemble (3). Similarly, CMIP6/ISIMIP3b simulations may modify the magnitude and spatial distribution of regional drought signals because of differences in climate sensitivity, large-scale circulation responses, precipitation projections, and bias-adjustment methods relative to CMIP5/ISIMIP2b. Higher-resolution regional climate model ensembles, such as EURO-CORDEX, may further refine the spatial expression of drought mechanisms, particularly in mountainous, snow-influenced, and coastal regions where topography, snow accumulation and melt, and precipitation-phase transitions are important (4). Thus, the quantitative projections reported here are specific to the selected CMIP5/ISIMIP2b RCP4.5 ensemble, whereas the process-based drought-typology framework is transferable to other scenario and model ensembles. In addition, the framework can be applied to outputs from alternative hydrological and land-surface models, enabling assessment of uncertainties arising from differences in model structure, parameterization, and process representation, including runoff generation and snow dynamics.Finally, the exclusion of anthropogenic influences such as land use change and water withdrawals may limit process realism at regional scales.

L389-390: This sentence on the Zenodo data repository should be moved to the Data availability section.

Authors' response #12: We thank the reviewer for this helpful suggestion. We have added a Data Availability section before the Appendix, including the relevant information on the datasets used in this study.

References

[1] Thakur, V. *et al.* Unveiling the impact of potential evapotranspiration method selection on trends in hydrological cycle components across europe. *Hydrology and Earth System Sciences* **29**, 4395–4416 (2025). URL `https://hess.copernicus.org/articles/29/4395/2025/`.

[2] Brunner, M. I., Van Loon, A. F. & Stahl, K. Moderate and severe hydrological droughts in europe differ in their hydrometeorological drivers. *Water Resources Research* **58**, e2022WR032871 (2022).

[3] Lehner, F. *et al.* Projected drought risk in 1.5 c and 2 c warmer climates. *Geophysical Research Letters* **44**, 7419–7428 (2017).

[4] Jacob, D. *et al.* Euro-cordex: new high-resolution climate change projections for european impact research. *Regional environmental change* **14**, 563–578 (2014).