We thank both reviewers for their valuable comments and constructive suggestions, which helped to improve the clarity, rigor, and overall impact of the manuscript.

In the following, Reviewer 1's comments are shown in plain text, and our responses are provided in italics. Changes made in the revised manuscript are indicated in quotation marks and shown in green.

The study analyzed the hydrological drought characteristics (duration, severity, intensity, and occurrence) under climate change scenarios (RCP 4.5/8.5).

According to my revision of the article, it lacks severe rigor, mainly in the methods section (see my comments below). My recommendation in the current status is that the article should be rejected.

Response

We thank the reviewer for their valuable time dedicated for reviewing the manuscript. In the revised manuscript, we have substantially reorganized Section 3 to clearly separate the identification of drought events from the calculation of their characteristics, thereby improving clarity, reproducibility, and alignment with the Results and Discussion.

The revised Methods section is now structured as follows:

3.1 Hydrological drought events

3.1.1 Hydrological drought identification

3.1.2 Hydrological drought characteristics

3.2 Hydrological drought classification

The section 3.1 has been divided into two new subsections: "3.1.1 Hydrological drought identification" and "3.1.2 Hydrological drought characteristics", which now clearly distinguish between drought identification based on streamflow anomalies using a threshold-based approach (Brunner et al., 2022, 2023; Van Loon, 2015; Van Loon & Laaha, 2015) and the characterization of drought events in terms of seasonality, duration, severity, minimum flow and occurrence.

We further clarify that drought characteristics are an integral part of hydrological drought event identification in an event-based drought analysis framework (Brunner et al., 2022, 2023; Gesualdo et al., 2024; Van Loon & Laaha, 2015). Therefore, these characteristics were included in the hydrological drought event definition and are necessary to fully describe and quantify each identified hydrological drought event.

This reorganization and clarification in the method section together with the reviewer 2 feedback significantly improved the clarity, rigor, and reproducibility of the methodology and better align the Methods section with the Results and Discussion.

Major revision

The study does not provide a clear definition of how the researchers are measuring drought. Are they using a streamflow drought index? I think not. Because the figures of the results display absolute values in millimeters (mm). Or, are they just analyzing the streamflow variable? This step is crucial for what is then analyzed.

Response

We thank the reviewer for their comment and for the opportunity to clarify our methodology. In this study, hydrological drought is not quantified using a standardized drought index but is identified directly from the streamflow time series using a variable threshold-level approach (Van Loon & Laaha, 2015).

Hydrological drought events are defined when the smoothed daily streamflow falls below a variable threshold corresponding to the 20th percentile of flow, calculated for each day of the year using a ±15-day moving window. This approach focuses on streamflow anomalies rather than normalized index values.

Streamflow values and hydrological drought severity are normalized by the contributing catchment area to express drought minimum flow and severity in millimeters (mm). Accordingly, drought severity represents the cumulative streamflow deficit per unit area (mm per event).

In the original manuscript, drought characteristics were included within the drought event identification subsection, which may have made the section less visible. In the revised manuscript, we have subdivided Section 3.1 into two subsections: "3.1.1 Hydrological drought identification" and "3.1.2 Hydrological drought characteristics." This reorganization presents the definitions and computation of drought seasonality, duration, and severity more clearly and separately, making it easier for readers to follow and ensuring consistency with the presentation of results.

We now specified in the manuscript as following:

"3.1 Hydrological drought events

3.1.1 Hydrological drought identification

Hydrological drought events in this study are defined as periods of abnormally low streamflow relative to the long-term seasonal distribution, using daily streamflow time series as the primary variable. We apply the variable threshold-level approach (Van Loon and Laaha, 2015) that is suitable for catchments with a seasonal streamflow regime.

The variable thresholds used to define droughts are computed from the simulated streamflow separately over a 30-year window for both historical and future periods. This approach results in a time-varying threshold for each future window and reflects the assumption that water management practices and hydrological systems gradually adapt to evolving climate conditions, following the method proposed by (Vidal et al., 2012).

First, the daily streamflow time series is smoothed using a centred 30-day moving window (±15 days) to reduce short-term variability and minimize the occurrence of dependent events (Fleig et al., 2006; Gesualdo et al., 2024). This smoothed streamflow series is then used for drought identification.

Second, the variable drought threshold is computed from the smoothed series using the 20th percentile of streamflow for each calendar day of the year. This percentile was computed for each day of the year based on the rolling time series of streamflow 15 days before and after the day of interest and the drought event is defined when the values of the smoothed streamflow time series fall below the variable drought threshold (Brunner et al., 2022a; Van Loon and Laaha, 2015).

Previous studies which implemented a sensitivity analysis on the impact of the drought threshold and moving window on drought characteristic (number of events, minimum flow, total deficit, and duration) found that the number of events and the duration of the event was to some degree sensitive to the choice of the threshold, and the event total deficit and minimum flow showed minimal variation with changes in the threshold and moving window length (Gesualdo et al., 2024). In this study, we use the threshold of 20th percentile which was set in different European and high elevation catchments drought analysis studies (Brunner et al., 2022a; Van Loon and Laaha, 2015)."

The results indicate that the methodology is incomplete. The methodology does not fully address the findings presented in the results. For example, the core of the article is the analysis of the characteristics of drought (duration, intensity, severity, etc), but none of them are declared in the methods section. All the above makes it very hard to follow what then is coming in the results and discussion.

Response

We thank the reviewer for this comment. In the revised manuscript, drought characteristics are now presented in a dedicated subsection ("3.1.2 Drought characteristics") to make them more visible and easier to follow.

"3.1.2 Hydrological drought characteristics

The duration (in days) is the number of the consecutive days during which the smoothed streamflow series was below the drought threshold and hydrological drought events with more than 30days duration were selected for the analysis. The number of events is the number of hydrological drought events occurred in the study period. The severity, in mm/event, that is drought volume or the total deficit, is the area between the daily threshold and the smoothed streamflow time series normalized by the catchment area (Brunner and Stahl, 2023; Gesualdo et al., 2024). The minimum flow, in mm, during the drought event is also presented in this study and is normalized by the catchment area (Brunner and Stahl, 2023; Gesualdo et al., 2024).

Drought event seasonality describes the time when drought events peaks are most likely to occur during the year. Following (Von Matt et al., 2024), we quantified seasonality using the day of the year (DOY), which ranges from 1 to 366. For each identified drought event, we recorded the day on which streamflow reached its minimum (the date of the lowest flow within the drought event) as the event's DOY. This DOY series over the study period reflects when drought peaks tend to occur during the year. To transform these discrete DOY values into a smooth, continuous representation of drought seasonality, we applied Gaussian kernel density estimation (KDE) (Von Matt et al., 2024). KDE was performed in R using the tidyverse package (Wickham et al., 2019). This method produces a continuous density curve that highlights the most likely periods of drought during the year. We computed seasonality separately for the reference and future periods for each of the 13 models over our 11 catchments, allowing us to compare how the timing of drought events minimum flow may shift or change under future conditions.

Many studies determine the peak timing of hydrological drought events and associate the drought events based on the date of minimum streamflow (e.g. Brunner et al., 2022a, 2023) given the importance of seasonal distribution of the minimum flow in the rivers especially for hydropower production. In Alpine catchments, hydrological regimes are strongly influenced by snow accumulation and melting processes. High flows typically occur during the snowmelt season (spring–summer), and for prolonged drought events, the timing of minimum streamflow can be shifted relative to the period of maximum water deficit. Consequently, the minimum flow of hydrological drought events may occur during the low-flow season (winter or early spring) and not align with the period of greatest deficit (difference than threshold) especially for events occurring longer than one season. To account for this, we evaluated drought characteristics using multiple metrics for the seasonal attribution. Results based on the date of minimum flow are presented in the main paper, while analogous results based on the date of maximum deficit are provided in the supplementary material."

Other comments.

In the title, instead of using just "drought", it should be replaced by "hydrological drought". Because drought is a broader concept, of which hydrological drought is just one type. Besides, in this study, hydrological drought is analyzed.

Response:

Thank you for your valuable feedback. The title has been updated to:

"Seasonal shifts in hydrological drought characteristics and their drivers in Italian alpine catchments under climate change**"**

Methods

Drought identification.

What is the specific definition of hydrological drought in this case? Instead of just referencing it, you need to provide a clear definition here. The text discusses a time series variable, but it does not specify which variable is being referred to. Should I assume that the variable in question is a streamflow anomaly?

Response:

We thank the reviewer for their feedback. We have revised Section 3.1.1 ("Hydrological drought identification") to explicitly state that hydrological drought is identified from streamflow anomalies and to clearly define the variable used and the threshold-based method.

“3.1.1 Hydrological drought identification

Hydrological drought events in this study are defined as periods of abnormally low streamflow relative to the long-term seasonal distribution, using daily streamflow time series as the primary variable. We apply the variable threshold-level approach (Van Loon and Laaha, 2015) that is suitable for catchments with a seasonal streamflow regime.

The variable thresholds used to define droughts are computed from the simulated streamflow separately over a 30-year window for both historical and future periods. This approach results in a time-varying threshold for each future window and reflects the assumption that water management practices and hydrological systems gradually adapt to evolving climate conditions, following the method proposed by (Vidal et al., 2012).

First, the daily streamflow time series is smoothed using a centred 30-day moving window (±15 days) to reduce short-term variability and minimize the occurrence of dependent events (Fleig et al., 2006; Gesualdo et al., 2024). This smoothed streamflow series is then used for drought identification.

Second, the variable drought threshold is computed from the smoothed series using the 20th percentile of streamflow for each calendar day of the year. This percentile was computed for each day of the year based on the rolling time series of streamflow 15 days before and after the day of interest and the drought event is defined when the values of the smoothed streamflow time series fall below the variable drought threshold (Brunner et al., 2022a; Van Loon and Laaha, 2015).

Previous studies which implemented a sensitivity analysis on the impact of the drought threshold and moving window on drought characteristic (number of events, minimum flow, total deficit, and duration) found that the number of events and the duration of the event was to some degree sensitive to the choice of the threshold, and the event total deficit and minimum flow showed minimal variation with changes in the threshold and moving window length (Gesualdo et al., 2024). In this study, we use the threshold of 20th percentile which was set in different European and high elevation catchments drought analysis studies (Brunner et al., 2022a; Van Loon and Laaha, 2015).”

Hydrological drought classification

It is not clear what the purpose of using this classification is. Then in the results, these types of drought are called drivers and analyzed as such. How could the variable analyzed be the driver of the same event (drought)?

Response:

We thank the reviewer for raising this important conceptual point.

The purpose of the drought classification is not to treat streamflow as the driver of hydrological drought, but to diagnose the dominant hydrometeorological processes controlling each identified hydrological drought event (identified from streamflow anomalies). Following the framework proposed by Brunner et al. (2022) and Van Loon and Van Lanen (2012), drought events are classified using hydroclimatic information (precipitation deficits, snow availability, and temperature conditions) that explains the development of each streamflow drought event.

In this context, the term "driver" refers to the dominant drought-generating process (e.g., rainfall deficit–driven, snow-controlled, or complex compound events), rather than to the streamflow variable itself. To avoid conceptual ambiguity, we have clarified throughout the manuscript that "hydrological drought types" and "hydrometeorological drivers" describe the same process-based classification framework.

We have revised Section 3.2 to explicitly state that the classification assigns each hydrological drought event (identified from streamflow anomalies) to one of eight drought types based on hydroclimatic drivers, and we have adjusted the terminology in both the Methods and Results sections to ensure consistent interpretation.

"3.2 Hydrological drought drivers

We applied a standardized drought classification scheme that assigns each identified hydrological drought event to one of eight hydrological drought drivers based on their hydroclimatic information (i.e. precipitation deficits, snow availability, and temperature conditions) and their seasonal context (Brunner et al., 2022b; Van Loon, 2015; Van Loon and Van Lanen, 2012). In the first step, hydrological drought events, identified in Section 3.1.1, are separated into rainfall-driven and snow-driven categories. Rainfall-driven droughts are defined by precipitation deficits occurring shortly before or during the drought period. Within this branch, three subtypes are distinguished: (i) rain-to-snow season droughts, which begin with a summer rainfall shortage (Jun-Sep) but persist into autumn (Sep-Oct) when temperatures fall below 0 °C; (ii) wet-to-dry season droughts, which emerge outside summer but extend into the dry season (Jun-Sep), when evapotranspiration intensifies deficits; and (iii) rainfall deficit droughts, when neither of the transition conditions applies. Snow-driven droughts are considered when no proximal rainfall deficit is detected and are further subdivided according to snowpack and temperature conditions. If the drought occurs during the snow season (Nov-Mar) and snow accumulation is possible (temperatures <0 °C), the event is classified as a cold snow season drought. If temperatures are above freezing but snow had accumulated earlier, the event is categorized as a warm snow season drought. Outside of the snow season, droughts are defined as snowmelt droughts when snowpack is insufficient to sustain spring flows, or as glacier melt droughts when glaciers are present in the catchment and the drought coincides with the melt season (Jul-Sep). Finally, when multiple processes act together or no single driver dominates, the event is assigned to the complex drought class. This framework allows consistent attribution of drought events to hydroclimatic drivers across different elevations and climate regimes. The classification scheme is illustrated in Figure A1."