

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 2'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 authors present an assessment of seasonal shifts in drought characteristics and drivers with reference to the Adige catchments and 10 sub-basins therein.

While the evolution of drought metrics in relation to climate change has been explored from several work, the very concept of driver-based categorization of hydrological drought is, to this day, severely under-explored while it offers great potential for drought prediction and management. For these reasons, I believe the work is timely and a valuable contribution to the scope of NHESS.

What I liked about the paper is the attempt at a spatial characterization of drought metrics and driver in a relatively narrow and morphologically complex domain. The amount of climate models employed in the analysis is sufficient, and not overwhelming compared to the size of the study. The results presented in the paper are consistent with existing literature and reflect the specificities of the study area. I think this is a (rightfully!) very ambitious work, and believe that its potential has not been fully tapped, for reasons I will try to enumerate in the following. I will follow the order of the paper and try to convey the relevance of each comment directly inside it. I think the work requires major revision to clarify some methodological choices, their implications in the results and to ultimately amplify its impact and relevance to the community.

We thank Dr. Andrea Galletti for their valuable time dedicated for reviewing the manuscript and we especially recognise their familiarity with the study area and expertise in drought processes in the mountainous domain. Their feedback contributed to better emphasize the relevance and impact of our work.

1. The abstract ends talking about the need for adaptation strategies. While obviously true, and while it is good to mention the practical implications of a study, I think these are way beyond the scope of this paper. Indeed, I would not request the Authors to detail on what kind of strategies should be developed based on their findings. More simply, I suggest focusing on the implications of the results actually presented (shifts in drivers and metrics).

Response:

We thank the reviewer for this suggestion. In the revised manuscript, we modified the final part of the abstract to better emphasize the projected shifts in hydrological drought characteristics and their dominant hydrometeorological drivers under future climate conditions. We also added a statement highlighting the consistency of the results across the two event attribution approaches (minimum flow and maximum deficit), thereby strengthening the robustness of the identified seasonal shifts. However, in the final sentence, we retained a broader concluding remark to preserve a general perspective on the potential relevance of the study's findings.

Old sentence:

“Drought peaks exhibit a bimodal pattern, occurring primarily in spring and summer, with summer peaks projected to shift earlier under future warming. Drought severity rises by more than 60% in winter and spring at high elevations, while duration remains stable. These findings highlight the need for adaptation strategies that account for both seasonal and driver-specific responses to sustain Alpine water systems.”

New sentence:

“Drought peaks exhibit a bimodal pattern, occurring primarily in spring and summer, with summer peaks projected to shift earlier under future warming. Drought severity rises by more than 60% in winter and spring at high elevations, while duration remains comparatively stable (i.e. between -20% and +20% overall). Seasonal drought projections are broadly consistent under alternative event attribution approaches based on minimum flow and maximum deficit, confirming the robustness of the identified seasonal shifts, although some differences emerge for long-duration droughts spanning multiple seasons. These findings demonstrate that future climate change will substantially alter both the seasonality and dominant hydrometeorological drivers of hydrological drought in Alpine catchments, with differences across elevation gradients. Results may be relevant for planning of future adaptation strategies and design specific responses to sustain Alpine water systems.”

2. Though understandable, I don't really like the term "lower-elevation hydrological regime". It implies a contrast with a high-elevation regime that not all readers might be familiar with. I suggest using a more general terminology (such as rainfall-dominated or pluvio-nival, depending on the Authors' opinion and the message they want to convey)

Response:

We thank the reviewer for this comment. We agree that the expression “lower-elevation hydrological regime” may be ambiguous for readers not familiar with elevation-based runoff regime classifications.

We revised the abstract to explicitly refer to runoff-generating processes (i.e. from snow/glacier-dominated toward rainfall-dominated streamflow regimes). We also revised the whole manuscript to ensure consistency.

Old sentence:

“Declining snow and warmer winters, which increase rainfall at the expense of snowfall, are shifting Alpine catchments toward lower-elevation hydrological regimes.”

New sentence:

“Declining snow and warmer winters, which increase rainfall at the expense of snowfall, are shifting Alpine catchments from snow- and glacier-dominated streamflow regimes toward rainfall-dominated streamflow regimes.”

3. The introduction presents some of the "ingredients" to the study: climate change effects on mountain river regimes, their implications for drought in mountain regions. It then cites (55-65) different drought types (per Brunner 2022 and other studies), sharply concluding that the spatial and elevational dependence of such drivers is underexplored. Finally, some emphasis is put on cryospheric processes related to drought and their uncertain evolution under continued warming. While agreeing with all of the above, I think that a clear need to understand drivers and metrics of drought in relation to climate change does not yet

emerge from the introduction. Put in other words, what is the value of *jointly* analysing drought drivers, metrics, and the effects that climatic change has on them? this would offer a stronger lead into the research questions.

Response:

We thank the reviewer and we agree with his comment. We have added a paragraph in the Introduction to better motivate and highlight the research questions.

New paragraph:

“Several studies employing a joint analysis of hydrological drought characteristics (e.g., occurrence, severity, and duration) and their hydroclimatic drivers have highlighted the importance of understanding the processes governing hydrological drought generation (Brunner et al., 2019, 2022a). In the context of climate change, such an integrated approach enables the assessment of how projected alterations in hydroclimatic processes may influence both the characteristics of hydrological droughts and their underlying drivers. Only few studies address the drivers of the hydrological drought in the Italian Alpine despite the valuable insights that can provide for planners and stakeholders especially under already reported decreasing trend in snow and glaciers accumulation (e.g. Avanzi et al., 2024; Bozzoli et al., 2024; Leone et al., 2025). Our aim is to address this gap, and jointly investigate the seasonality, characteristics, and dominant drivers of hydrological drought events in the Adige River basin, a representative Italian Alpine catchment spanning diverse elevations. Using an ensemble of climate model simulations under RCP4.5 and RCP8.5, we assess projected changes in drought seasonality, duration, number of events, severity (i.e. total deficit) and intensity (i.e. minimum flow) and the dominant hydrometeorological drivers from the reference period (1989-2018) to the near-future (2020-2049), mid-future (2045-2074), and far-future (2070-2099).”

4. line 90: I think the area and minimum elevation reported are related to the Adige at its outlet, not at the Villa Lagarina section.

Response:

Thank you for this comment. We clarify that the area and minimum and maximum elevation values reported in Line 90 refer to the Trentino-Alto Adige region, not specifically to the Adige River basin at the Villa Lagarina section. The drainage area of the Adige River at the Villa Lagarina gauge (10,160.74 km²) was reported separately in Table A1.

To avoid any confusion, we have revised the text in the manuscript to explicitly describe the area, min and max elevation of the Adige river basin at Villa Lagarina closure. In addition, Figure 1 was expanded with panel (b) to better illustrate the location of the study catchments and emphasize their relevance within the Alpine domain.

New paragraph:

“The Adige River basin in the Trentino-Alto Adige region, northeastern Italy, is an Alpine River basin. It features a wide range of landscapes, from glaciers in the north to flat plains in the south. Agricultural areas are mainly concentrated along the Adige River and across the southern plains. The Adige river basin covers approximately 10,161 km² at the Villa Lagarina closure (fig.1), with elevations ranging from 157 meters to 3854 meters above sea level (Fig 1.a). The first quartile elevation is 1210 meters, and the third quartile is 2171 meters, highlighting the basin’s predominantly mountainous character. The region plays

a key role in agricultural production and hydropower generation, with hydropower production reaching 4,321 GWh in Trentino (2014-2016; (APRIE & PAT, 2022); and 7,741 GWh in Alto Adige in 2024 (EURAC, 2026). It includes around 146,100 hectares of farmland, based on the Corine Land Cover map (CLC18), and have several reservoirs that are used for energy production (Bouabdelli et al., 2025; Morlot et al., 2024).”

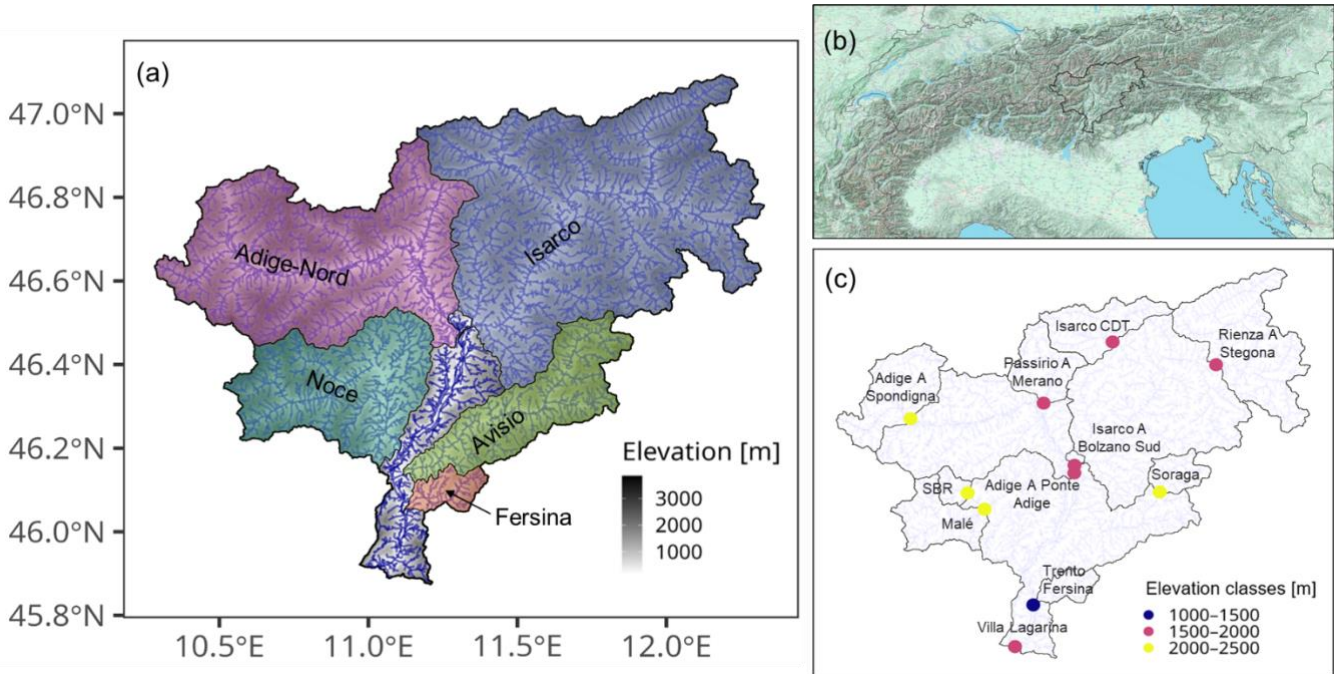


Figure 1. (a) Elevation model of the Adige River basin showing topographic variability and the major contributing catchments: Adige-Nord, Isarco, Noce, Avisio, and Fersina. Shaded colors represent catchment boundaries. (b) Location of the Adige River basin. (c) Elevation distribution of the 11 sub-catchment outlets used for the drought analysis in this study. Isarco CDT refers to Isarco a Campo di Trens and SBR refers to San Bernardo Rabbi.

5. lines 99 and 105 state that the work is focused on 11 natural catchments. While being in stark contrast with line 94, and with my knowledge of the presented sub-basins, perhaps here the Authors are meaning that they do not model anthropogenic alterations as a design choice?

Response:

We agree with the reviewer on the misleading term of ‘natural catchments’ we removed the term natural and we would like to evidence that we choose the 11 catchments as not highly influenced (i.e. not immediately downstream the main larger dams in the area). However, the dam and anthropogenic alteration have been included in the model as per (Morlot et al., 2024, Bouabdelli., et al 2025). We corrected the sentence as the following.

New sentence:

“All streamflow gauges selected in this study correspond to gauges not immediately downstream the main larger dams in the area, ensuring that these catchment flows are not influenced by hydropower reservoirs or other anthropogenic alterations (Table A1).”

6. I would specify that Crespi 2021 does not contain observations, rather an observation-based gridded dataset, though it is somewhat implied by providing the 250m resolution.

Response:

Many thanks for your comment. We corrected the sentence as following:

Old sentence:

“These datasets were downscaled to 1 km using high-resolution (250 m) ground-based observations for the Trentino-Alto Adige region provided from Crespi et al., (2021).”

New sentence:

“These datasets were downscaled to 1 km using high-resolution (250 m) ground-based gridded dataset for the Trentino-Alto Adige region provided from Crespi et al., (2021).”

7. line 116: A-HDT seems to reflect Hydrological Digital Twin (?) instead of Digital Hydrological Model (DHM?). perhaps check.

Response:

The Adige hydrological digital twin (A-HDT) model was introduced in Morlot et al (2024) and was also used in Bouabdelli et al (2025) analysis. Which means that we used the calibrated parameters of the A-HDT to simulate the streamflow at the different time periods. The definition was specified in line 116.

Old sentence (line 116):

“For the drought analysis, we used the Adige Digital Hydrological Model (A-HDT; Morlot et al., 2024) to run simulations of water cycle components (runoff, actual evapotranspiration, soil moisture and snow water equivalent), which had been previously calibrated and validated against discharge observations from 33 gauging stations across the Adige River basin.”

8. lines 132-135: From my understanding, streamflows are moving averaged (30 days, i assumed centered to 15 before and 15 after?). Then, a climatological "reference year" of Q20s is computed. I do not understand if each Q20 is really not referring to its own calendar day or also considers the +-15 window, as stated in line 134. Would this mean that the same window is adopted before for smoothing and later for picking the Q20? in any case, the explanation could be clearer. Also, the authors do not mention (or I missed it) whether the thresholds are computed with respect to observation or to modelled data. I assume the latter, since it is done for historical and future time windows. Do the authors imply that the variable threshold changes for each future time window? if so, did they explore the implications on their result, as opposed to a fixed window computed on the historical 30 years?

Response:

We thank the reviewer for this comment. We agree that the description of the drought identification procedure required clarification as reviewer 1 highlighted, and we have revised the Methods section accordingly.

YES, as stated in line 134 and as pointed out by the reviewer the Q_{20} , is computed also considering ± 15 days window centred in the day of interest, of the smoothed 30-day moving averaged (± 15 days) streamflow series.

Using the fixed window computed on the historical 30 years assumes that the perception of drought remains unchanged, meaning that normals are evaluated in the same way in the future as in the reference period. While drought is defined as a deviation from normal conditions, these normals may evolve over time; therefore, a moving 30-year reference period can be used to derive a variable drought threshold, implicitly representing adaptation to long-term changes in the hydrological regime (Vidal et al., 2012; Wanders et al., 2015). The implications of using such variable thresholds for future drought projections have been explored in previous studies (e.g., Wanders et al., 2015), showing that accounting for gradual adaptation can influence projected drought characteristics compared to stationary thresholds based on historical periods.

We have also clarified in the revised manuscript that drought thresholds are period-specific and derived from modelled streamflow for each time window, and we have improved the explanation of the moving windows to avoid ambiguity.

New paragraph:

“The variable thresholds used to define droughts are computed from the simulated streamflow 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 average (± 15 days) to reduce short-term variability and minimize the occurrence of dependent drought events (Fleig et al., 2006, Gesualdo 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 (i.e. Brunner et al., 2021; Gesualdo et al., 2024).”

References

*Vidal, J.-P., Martin, E., Kitova, N., Najac, J., & Soubeyroux, J.-M. (2012). Hydrology and Earth System Sciences Evolution of spatio-temporal drought characteristics: validation, projections and effect of adaptation scenarios. *Hydrol. Earth Syst. Sci.*, 16, 2935–2955. <https://doi.org/10.5194/hess-16-2935-2012>*

*Wanders, N., Wada, Y., & Lanen, H. A. J. Van. (2015). Global hydrological droughts in the 21st century under a changing hydrological regime. *Earth Syst. Dynam.*, 6, 1–15. <https://doi.org/10.5194/esd-6-1-2015>*

9. line 136+: I think the choice of the threshold (quantile level) and moving average window have a clear effect on the statistics of the droughts that they identify. They affect the severity, here defined as the deficit from the reference, as well as the population of events (duration-frequency). Moreover, droughts driven by different processes do have different hydrological signatures, therefore even the dominant drivers might be affected by this choice. While the values chosen (Q20 and 30 day moving average) are absolutely reasonable, I suggest to not downplay their implications, and rather present them as a reasonable design choice.

Response:

We thank the reviewer for this comment and agree that the choice of the percentile threshold and the moving average window influences the identified drought event identification, including event duration, frequency, severity, and even drought drivers. To provide context and support for our choice, we referred to Gesualdo et al. (2024), who performed a sensitivity analysis of the drought threshold (10th, 15th and 20th percentiles were tested) and smoothing window (10days, 20days and 30days) on drought characteristics. They found that lower thresholds or shorter moving windows resulted in fewer events with shorter durations, smaller deficits, and lower intensity. However, drought deficit and intensity showed minimal variation across reasonable threshold and window selections. Based on the sensitivity analyses and to remain consistent with hydrological drought studies in Europe (Fleig et al., 2006; Brunner et al., 2021, Brunner et al, 2022), we selected a Q20 variable threshold and a 30-days smoothing window. We acknowledge that any specific choice remains somewhat subjective, but it represents a reasonable methodological design that ensures comparability with previous European studies and yields a representative drought population for the subsequent analysis.

As we mentioned previously, we have improved the Methods section to clarify the procedure for drought identification and the rationale behind the methodological choices, including the selection of the Q20 threshold and 30-day smoothing window.

Old sentence:

“According to (Gesualdo et al., 2024a), while the choice of the threshold and moving window for the definition of the drought events does not impact significantly the severity and intensity of the drought events, it has an effect on their number and duration.”

New sentence:

“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, 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 intensity 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., 2022; Van Loon & Laaha, 2015).”

10. line 143: this definition of intensity is not the most common. Here, it is presented as the absolute minimum flow during each event, regardless of when it happens. More often, intensity is presented as the (average or largest) gap between reference

curve and event. Perhaps the authors could elaborate on this choice and its implications. Then, I really do not understand the concept of "highest intensity" provided soon after in line 144, and whether it is used in the paper or not. Finally, if runoff is given in mm it should already be considered catchment-specific, so I do not see the point of normalising it again vs the catchment area.

Response:

Thank you for your comment. We agree with the reviewer comment that there are multiple definitions of drought intensity in the literature. In this study, as presented in the Methods section, we followed the definitions proposed by Brunner and Stahl (2023) and Brunner et al. (2023), where hydrological drought intensity is defined as the minimum flow (in mm) reached during each hydrological drought event. According to this definition, the smaller the minimum flow value, the more intense the hydrological drought event is considered. Similarly, Gesualdo et al. (2023) defined drought intensity as the absolute value of the minimum flow during a hydrological drought event. In the revised manuscript we use the term "minimum flow" and not intensity.

Regarding the normalization of streamflow, our motivation was to enable intercomparison of drought events among catchments, particularly along the river network and between nested catchments. For example, the minimum flow volume at the Villa Lagarina (outlet of entire basin) is not directly comparable to that of the Fersina River, the Rienza River at the Stegona station, or the Isarco at Bolzano Sud catchment, due to their different contributing areas.

Therefore, to make results comparable across catchments, we normalized the total deficit and the minimum flow values by dividing these values by the contributing area of the corresponding catchment, in the same way commonly applied in flood analysis. This procedure allows a consistent quantification of minimum flow and total deficit across basins of different sizes. A similar normalization approach has also been adopted in previous studies (e.g. Brunner, 2021).

Brunner, M. I. (2021). Reservoir regulation affects droughts and floods at local and regional scales. Environmental Research Letters, 16(12), 124016. <https://doi.org/10.1088/1748-9326/ac36f6>

11. line 148: this is a key point. I hope I am getting the definition correctly and I apologise for my next comments if I missed parts or the entirety of it. Here, every drought is basically concentrated in its "peak low flow day". However, this does not take into account the natural hydrologic regime of the river. For the Adige, lowest flows are in late winter-spring; this means that any event that spans these seasons, even if it started months earlier or continued months later (as testified by durations of 60-120 days in fig 4), it would inevitably (or very likely) be attributed to a low-flow month. The main issue is that the majority of the deficit does NOT happen in these months, but rather in months of high (reference) flows, where the absolute deviation from reference can be much larger. Honestly, I do not really agree with this way of treating droughts as "point events", as too many subsequent results on seasonality depend on this and are treated as if each event was related to a specific season, and to that only. I encourage the Authors to explore the implications of this design choice, and if they choose to retain, more careful wording of the results is necessary, as they are mostly related to peak low flow and not to the full extent of the drought.

Likewise, even the link with drivers resents of the definition, and this should be clearly acknowledged when describing them. Alternatively, if the authors wish to preserve the single-day attribution of drought seasonality, perhaps as an alternative is to place the peak when the maximum relative deviation from reference flow occurs (which still doesn't talk about deficit magnitude, but I have nothing else on my mind now).

Response:

Thank you for this relevant and detailed comment. We agree with the reviewer that the date of minimum flow does not necessarily coincide with the date of maximum deficit. Our choice to use the date of minimum flow was made to ensure consistency and comparability with previous studies that adopted the same approach for the seasonal analysis of hydrological drought events, as discussed in the manuscript (Brunner et al., 2023). In addition, given the importance of the study region for hydropower generation and irrigation management under climate change, we selected minimum flow as a particularly relevant metric, as its seasonal variability and annual probability distribution provide useful insights for water management applications, especially for hydropower production and irrigation scheduling.

To address the reviewer's concern, we have now included an additional seasonal analysis in which hydrological drought events are associated with the date of maximum deficit rather than the date of minimum flow. These results are presented and discussed in Section 2 of the Supplementary Information. In the main manuscript, we retain the presentation based on minimum flow, while expanding the discussion to further clarify its relevance for water resources management in Alpine catchments.

We also updated the conclusion accordingly.

New paragraph in discussion

“Shifts in the timing distribution of minimum flows are expected to influence both hydropower production and irrigation scheduling, particularly around the two identified seasonal clusters. A reduced probability of drought peaks in late autumn and early winter may benefit hydroelectric generation. Majone et al., (2016) suggest that hydropower production could increase in the short to medium term due to higher water availability for plants located at higher elevations in the Adige River basin. In contrast, an increased probability of minimum flows during summer reflects a redistribution of runoff towards autumn and spring, which is likely to affect irrigation water management, particularly in the southern and southwestern valley areas of the Adige River (Napoli et al., 2025).”

New paragraph in discussion

“Changes in drought seasonality and in the relative contribution of different drought-generation processes may have direct implications for drought management and irrigation scheduling, particularly given the projected increase in winter runoff and decrease in summer flows under warming conditions and higher evapotranspiration. These shifts may negatively affect hydropower production during cold season droughts or snowmelt droughts, while potentially enhancing production in late spring or summer under earlier snowmelt and increased minimum flows, as well as improving winter generation when higher flows coincide with peak energy demand (Brunner & Naveau, 2023; Gaudard et al., 2014; Napoli et al., 2025).”

New paragraph in conclusion

“This redistribution of runoff suggests increasing water availability during winter but reduced availability during summer, potentially amplifying seasonal mismatches between water supply and irrigation demand under warmer conditions.

The seasonal shifts and intensification of hydrological droughts are strongly elevation dependent. These patterns are consistent across alternative event attribution approaches based on minimum flow and maximum deficit, confirming their robustness.”

“These transformations carry major implications for water management, hydropower, irrigation, and tourism, as shifts in minimum flow timing may reduce hydropower production during cold-season or snowmelt-deficit droughts, while potentially enhancing generation during earlier spring runoff or periods when increased winter flows coincide with peak energy demand. This highlights the need for adaptation strategies that account for both seasonal and elevational differences in drought response.”

Section 2 in the Supplementary information:

“2. Seasonal changes in hydrological drought characteristics under RCP future scenarios

Figure S1 presents the seasonal analysis of hydrological drought duration and its projected changes under the RCP scenarios, with drought events assigned according to the date of maximum deficit. During the reference period, the seasonal ranges of median drought duration obtained using this attribution method (Fig. S1 a to h) are similar to those derived when events are assigned according to their date of minimum flow.

However, the seasonal distribution of median drought duration differs between the two approaches. When droughts are attributed based on the timing of maximum deficit, median duration is longer in autumn, whereas attribution based on minimum flow results in longer median durations in winter. This difference is expected, as some drought events reaching minimum flow in winter may instead be assigned to autumn when classified by maximum deficit, reflecting the season in which the absolute difference between streamflow and the threshold level is greatest.

Overall, projected seasonal changes in drought duration based on maximum-deficit timing are broadly consistent with those obtained using minimum-flow timing. Nonetheless, under the RCP8.5 scenario in the mid- and far-future periods, the two attribution methods diverge: classification based on maximum deficit indicates increasing drought duration in spring and summer, whereas classification based on minimum flow suggests decreasing duration. This discrepancy likely reflects the behaviour of long-duration drought events spanning multiple seasons, which may reach their minimum flow in autumn while their maximum deficit occurs earlier, during summer or spring.

Median changes in drought duration based on maximum-deficit timing indicate a general increase in spring across all catchments under both the RCP4.5 and RCP8.5 scenarios (Fig. S1 k-o-s-w). Increases reach approximately 40% in most mid-elevation catchments during the mid-future period, rising to 60-80% in high-elevation western catchments in the far future. In contrast, median drought duration is projected to decrease in autumn across all catchments under both scenarios and future periods.

The projected spring increases and autumn decreases are consistent with shifts in event attribution toward these seasons when droughts are classified by their dates of maximum deficit, particularly for long-duration events. This reflects the greater

sensitivity of threshold exceedance during transitional hydrological periods, when snowmelt onset and rainfall events can substantially alter streamflow conditions. Because these processes mark transitions between low- and high-flow regimes, they strongly influence both the timing and magnitude of maximum deficits.

Figure S2 presents the seasonal analysis of hydrological drought severity (total deficit) and its projected changes under the RCP scenarios, with drought events assigned according to the date of maximum deficit. During the reference period, drought severity is generally greater in spring and summer when events are attributed based on maximum-deficit timing (Fig. S2 g-h), whereas attribution based on minimum-flow timing indicates higher severity primarily in summer. This difference is expected, as drought events spanning spring and summer may be assigned to later in the season when classified according to the timing of maximum deficit. As shown in Figure 2 of the manuscript, the highest density of projected hydrological drought events occurs in late spring and early summer.

Projected median changes in drought severity based on maximum-deficit timing are generally consistent with those obtained using minimum-flow timing. Both approaches indicate an increase in total drought deficit during winter (exceeding 100% in some catchments) and spring, along with a decrease in summer, particularly under the RCP8.5 scenario.

In autumn, however, the two attribution methods diverge. When droughts are assigned according to the date of maximum deficit, projected changes indicate an increase in total deficit under both scenarios, particularly in mid- and high-elevation catchments, with increases of approximately 20-40%. In contrast, attribution based on minimum-flow timing suggests only slight increases (0-20%) under RCP8.5 and decreases of up to 20-40% under RCP4.5.

As discussed in the manuscript, increases in total deficit during summer and autumn are likely associated with reduced snowmelt contributions to streamflow, which lower discharge relative to the threshold level, as well as rainfall deficits during these seasons that further intensify drought severity. These processes can shift the timing of maximum deficit and lead to stronger projected increases in drought severity when events are classified according to maximum-deficit timing.

Figure S3 presents the seasonal analysis of the number of hydrological drought events and their projected changes under the RCP scenarios, with drought events assigned according to the date of maximum deficit. During the reference period, the seasonal distribution of the median number of drought events slightly differs from that obtained when events are attributed based on the date of minimum flow. Specifically, the median number of events is higher in summer and autumn when using maximum-deficit timing (Fig. S3 e-h), particularly compared with the seasonal attribution based on minimum flow.

Projected changes in the mid- and far-future periods are broadly consistent between the two attribution methods in winter and spring, with both indicating increases in the number of drought events. However, the results diverge in summer and autumn, where attribution based on maximum-deficit timing generally indicates decreases compared with the patterns derived from minimum-flow timing. The narrower range of projected percentage changes also reflects the higher baseline median number of events during the reference period, resulting from the different seasonal distribution of drought events under the maximum-deficit attribution method.

These results suggest that the timing of maximum deficit is more sensitive to seasonal attribution than the timing of minimum flow. This is expected, as river discharge generally exhibits more stable seasonal timing, whereas daily deficit values derived from a variable threshold are more sensitive to short-term hydrological fluctuations and seasonal transitions, particularly under projections of longer-duration drought events.

Figure S4 presents the seasonal analysis of the minimum flow of hydrological drought events and its projected changes under the RCP scenarios, with drought events assigned according to the date of maximum deficit. Results based on maximum-deficit timing are broadly consistent with those obtained using minimum-flow timing, although slightly higher median values are observed in summer and autumn during the reference period (Fig. S4e-h).

Projected changes indicate decreasing minimum flow in summer and increasing minimum flow in spring and winter, with consistent patterns across both attribution methods. These results are in agreement with those presented and discussed in the main manuscript, confirming that the seasonal projections of minimum flow are less sensitive to the choice of event attribution method.”

12. paragraph 3.1.2 basically re-explains Brunner 2022. To make it more relevant, i would contrast-relate all decisions with the specificities of the Adige. Was any decision parameter changed with respect to Brunner's method? Are all quantities involved in the decisions basin-wide? what is the normal climatology of the Adige so that seasons such as wet-dry-snow can be put into more context?

Response:

Many thanks for this suggestion. We retained the same decision parameters as in Brunner et al., (2022) as this methodology has been tested across European catchments, including Alpine regions (Brunner et al., 2022, 2023; Janzing et al., 2026).

Within the category of hydrological drought events driven by rainfall deficits, three classifications are distinguished: (1) wet-to-dry drought, (2) rain-to-snow drought, and (3) rainfall deficit drought. The first two classes are designed to identify drought events driven by rainfall deficits that transition between hydroclimatic conditions.

The wet-to-dry classification describes events in which a rainfall deficit begins prior to summer and persists into the summer period (June–September). This situation may occur, for example, in the Adige catchment when spring and summer precipitation deficits are not compensated by snowmelt contributions, leading to streamflow falling below the threshold.

The rain-to-snow classification captures events that extend from summer (June–September) into autumn (September–October), during which the mean catchment temperature drops below 0 °C. Under these conditions, precipitation would typically fall as snow, allowing for potential accumulation; however, in the absence of precipitation, deficits persist. This class is therefore representative of prolonged rainfall (and snowfall) deficits extending into autumn. We agree with the reviewer that sensitivity analysis of each drought type should be checked for local specific study, but this is outside the scope the current paper.

Janzing, J., Wanders, N., vanTiel, M., & Brunner, M. I. (2026). Spatiotemporal dynamics of streamflow drought in the larger Alpine region. *Water Resources Research*, 62, e2025WR040503. <https://doi.org/10.1029/2025WR040503>.

13. the Authors say (179) that results are contrasted with precipitation and ET. is ET potential? how is it computed? And importantly, why not also contrasting them with temperature or temperature anomaly as T directly drives 2 decisions?

Response:

Many thanks for your remark. In the revised paper we corrected the sentence and spelled out that is Potential evapotranspiration (as also stated in Figure A3). The potential evapotranspiration was computed using Hamon model (Hamon, 1963), as illustrated in Morlot et al, (2024).

References: Hamon, W.R., 1963. Computation of direct runoff amounts from storm rainfall. Int. Assoc. Sci. Hydrol. Publ. 63, 52–62.

Similarly to potential evapotranspiration and precipitation, we have added now in the Appendix the changes in average temperature as suggested by the reviewer. And we discuss now the results accordingly. Below you can see the added sentences and figures.

New paragraph:

“For drought severity (Fig 4), the largest total deficits are generally associated with drought events with minimum flow in summer, particularly in *Passirio at Merano* and *Isarco CDT* (mid-elevation) under both scenarios, and in *Rienza at Stegona* (mid-elevation) under RCP4.5. This pattern is expected and likely reflects the combined effects of increased temperatures (FigA3), increased evapotranspiration (Fig A4), and reduced snow contribution followed by rainfall deficits in spring and summer (Fig A5) that can decrease the flow below the normal. These catchments are located at mid-elevations (1500-2000 m) which means that streamflow is sensitive to snow availability and snow melting.”

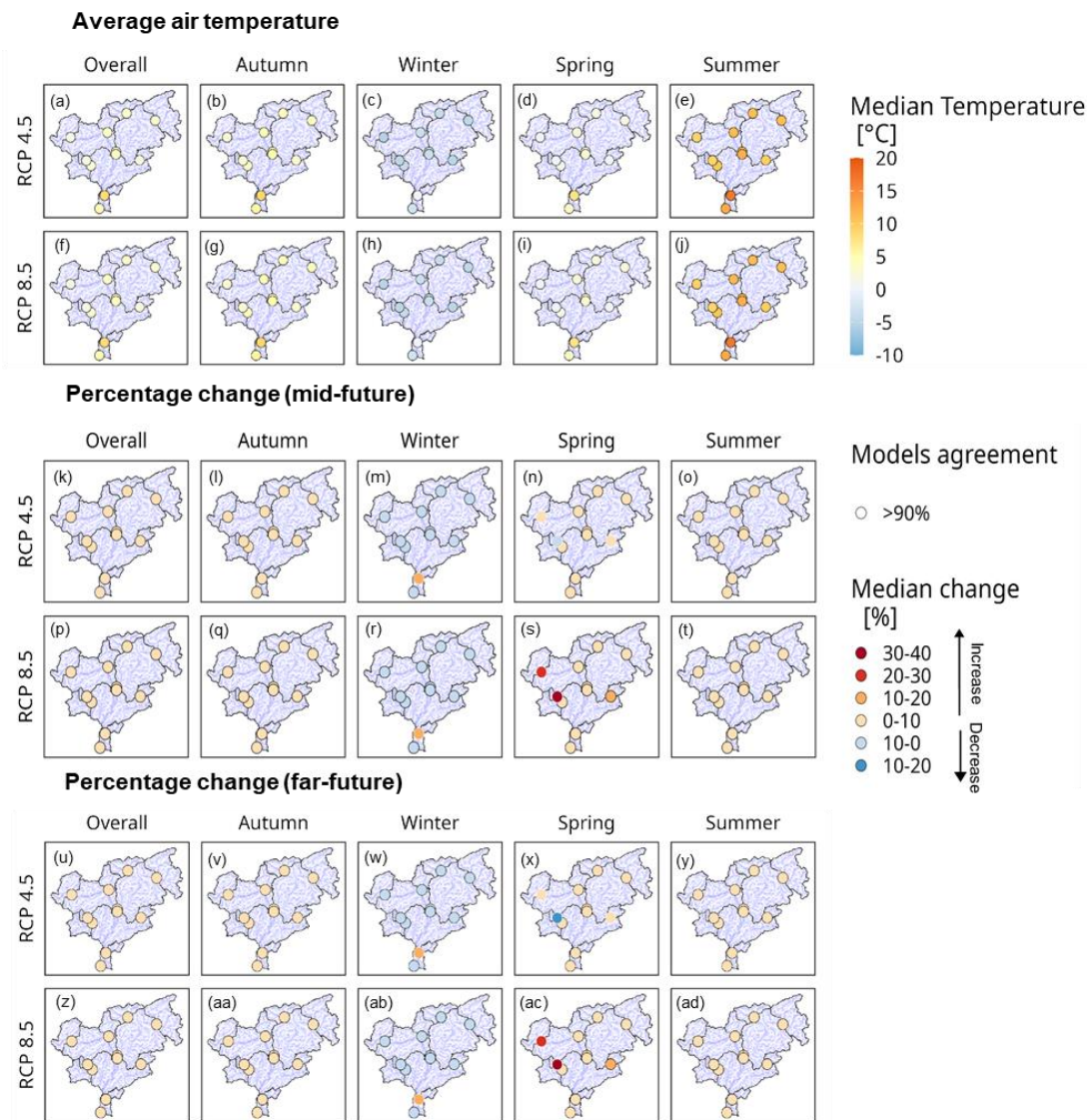


Figure A3: Average air temperature during the reference period (1989-2018), and the projected changes under climate change for the RCP4.5 and RCP8.5 scenarios for the mid (2045-2074) and far (2070-2099) future. Median values are shown in colour. For the percentage changes, agreement on the sign of change among models is indicated by black circles.

14. no letters in Fig 2 sub-panels. also y axis is "probability". Also I'd like having some (not all) months on the x axis, instead of calendar days, since the discussion is entirely seasonal. seasons would do as well.

Response:

Many thanks for your remark. Seasons delimitations are now added to the x axis to help the reader following the results.

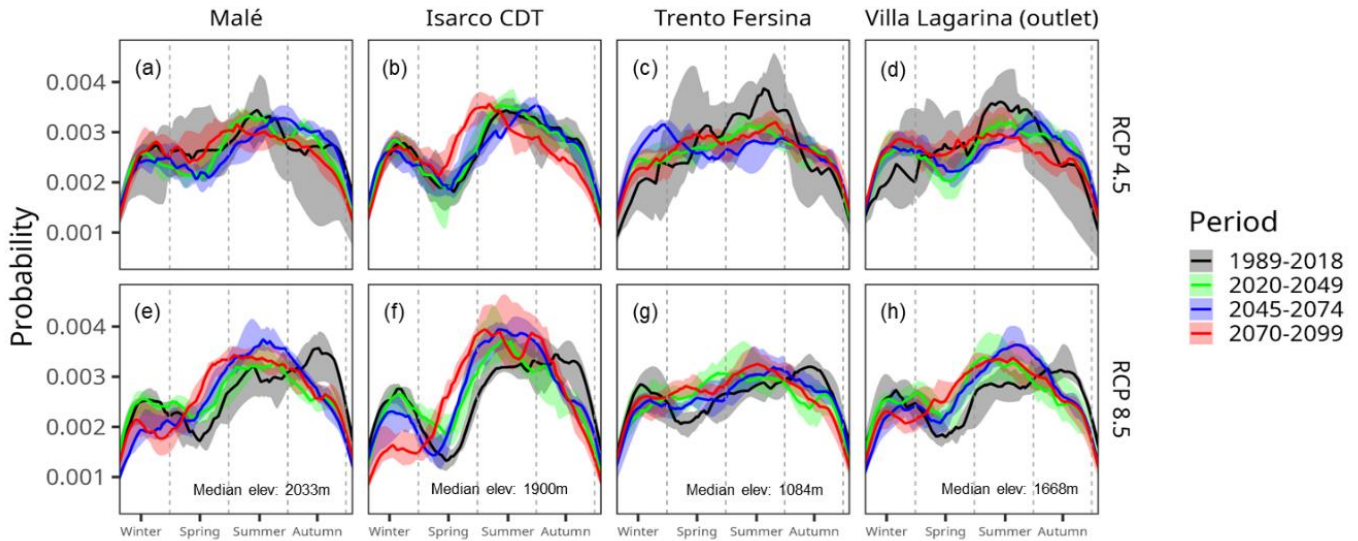


Figure 2: Seasonality of drought events peak timing (i.e. minimum flow during drought event). Shaded areas show the probability density of drought events for each day of the year across all 13 models for each catchment, with medians indicated. Solid lines represent the median across all models. Results are shown for RCP4.5 and RCP8.5 across all periods: reference period (1989 to 2018), near future (2020 to 2049), mid future (2045 to 2074), and far future (2070 to 2099). Isarco CDT refers to Isarco a Campo di Trens.

15. line 187: what supports the statement that single annual peak is characteristic of low elevation catchments? Does it imply that the peak related to spring melt is missing? Also, the behavior is not retained in RCP8.5 and even in 4.5 the variability envelop seems to still hint at a dual peak. Indeed, the Fersina also sees decent snow cover during winter, albeit it has no glaciers.

Response:

We agree with the reviewer's comment. In the original sentence, we intended to highlight that the bimodal (dual) annual peak tends to be more damped in lower-elevation catchments such as the Fersina basin, rather than implying the complete absence of a spring signal. We have revised the text accordingly to better reflect this point, explicitly acknowledging the residual spring peak suggested by the variability envelope and clarifying the role of snowmelt contributions.

Old sentence:

Both scenarios display broadly similar patterns in drought peak timing, except for the Fersina River during the reference period (1989-2018), where under RCP4.5 a single annual peak is observed, with probability rising to a maximum in August and decreasing thereafter (Fig 2.c). This behaviour is characteristic of lower-elevation catchments, consistent with the mean elevation of the Fersina basin (1084 m). However, projections indicate an emerging increase in winter drought probability in the mid-future period

New sentence:

“Both scenarios display broadly similar patterns in drought peak timing, except for the *Fersina* River during the reference period (1989-2018). Under RCP4.5, a dominant late-summer peak is observed, with probability rising to a maximum in summer and decreasing thereafter (Fig. 2c), although the variability envelope across the models still suggests a weaker secondary peak. This pattern may reflect the relatively low mean elevation of the *Fersina* basin (1084 m), where snowmelt contributions are less pronounced and more temporally diffuse compared to higher-elevation catchments. However, the presence of seasonal snow cover likely still contributes to the hinted spring signal. In future projections, an increase in winter drought probability emerges in the mid-future period, and the single-peak structure becomes less distinct, particularly under RCP8.5.”

16. line 202: How can the adopted definition for drought timing capture the likely occurrence of droughts caused by earlier snowmelt?

Response:

Many thanks for your comment. We have corrected the following sentence to explain better our point and avoid repetition.

Old sentence:

“Based on the median probability density of drought events, drought peaks cluster into two distinct seasons: a spring peak (February-mid-April) and a summer peak (May-September), with the highest probability concentrated in summer and the scenario differences appear mainly in the probability values, with higher probabilities under RCP8.5 indicating more frequent droughts than under RCP4.5. The transition between these two peak periods likely reflects recovery associated with snowmelt and spring rainfall and differences among scenarios and projected periods become more pronounced in summer. It is important to note that drought peak timing corresponds to the minimum flow during a drought event, after which recovery begins. Therefore, a shift in drought peak timing to earlier or later also implies a corresponding shift in drought recovery, which may be triggered by early snowmelt, glacier melt, or spring rainfall in the absence of rainfall deficits.”

New sentence:

“Based on the median probability density of drought events, drought peaks cluster into two distinct seasons: a late winter-spring peak (February-mid-April) and a late spring-summer peak (May-September). The highest probabilities are concentrated in summer with larger values under RCP8.5, indicating more frequent droughts in the summer season than under RCP4.5. One possible explanation for the transition between these two peak periods is streamflow increase driven by snow melting and/or spring rainfall.”

17. line 214: The term "persistency" is not appropriate since what is being presented is a PDF generated by 1-day events. even if some high probability persists, it is due to two events whose peak is nearby, not to a single, persistent, one.

Response:

Many thanks for your feedback. We corrected the term in the Manuscript and improved the interpretation.

Old sentence:

“In the Fersina basin, drought density does not decrease after the spring peak, suggesting persistent rainfall-driven drought events (Fig 2.g).”

New sentence:

“In the Fersina basin, drought densities are gradually continuous from the spring to summer (Fig 2.g). This continuous pattern can be related to lack of snow accumulation/melting and/or rainfall deficit that driven the hydrological drought events.”

18. San Bernardo Rabbi has 2 b's.

Response:

Many thanks for your relevant remark. We corrected the spelling in the Manuscript.

19. line 218: again, if we are talking about 1-day events, how does this link to the "month with highest drought probability"? For this, I'd rather analyze the number of "in drought" days that each month has -regardless of which events they belong to-, to provide a more objective measurement.

Response:

Many thanks for your suggestion and feedback. We decided to exclude figure 3 and its corresponding interpretation in the manuscript. To keep consistency in the whole manuscript, we kept only the seasonal analysis, and we removed the monthly analysis from the manuscript. Moreover, we also presented the results based on the dates of maximum deficit and not only the date of minimum flow, as pointed out by the reviewer.

20. for all section 4.2, I have found it pretty hard to follow all the changes and metrics with reference to one or more catchments. Between that, the RCP's, the seasons and the metric-change dicotomy, it can get overwhelming. have the authors thought about presenting their results by elevation classes (presented in the case study but rarely used after), instead of by-catchment? of course the images can stay unchanged.

Response:

Many thanks for your suggestion, we now commented the results by including the elevation classes close by the catchment name. We give here an example.

New Sentence

“Over the entire period (Fig 4.k.p), drought severity is projected to increase by 0-20% under RCP4.5 in the southern Adige, including *Malé* and *Soraga* (high-elevation) and *Fersina* (low-elevation) catchments, at the outlet of Isarco (*Isarco a Bolzano Sud*; mid-elevation) and Adige-Nord (*Adige a Ponte Adige*; mid elevation), and at the Adige outlet (*Villa Lagarina*; mid-elevation). Under RCP8.5, increases are projected across all sub-catchments and at the Adige outlet, except for the *Fersina*, where a slight decrease (0-10%) is projected. Under RCP8.5, increases are projected across all sub-catchments and at the Adige outlet, except for the *Fersina*, where a slight decrease (0-10%) is projected. For the mid-future period (2045-2074), the drought

severity increases in both winter and spring, with more pronounced changes in spring (Figure A6). Under RCP8.5, the total deficit exceeds 100% of increase at the *Isarco outlet* (mid-elevation) and *Soraga* (high-elevation) in winter, and in *Isarco CDT* and *Passirio at Merano* (mid-elevations) during spring.”

21. line 235: see my comment about annual hydrologic regime. being close to the annual minimum does not imply that the drought is severe.

Response:

Many thanks for your comment. As we explained above. We decided to exclude figure 3 and its corresponding interpretation in the manuscript as it can be overwhelming. The seasonal analysis is however maintained and the results of the seasonal changes in drought characteristics based both on the date of minimum flow and on the date of maximum deficit are now provided (please check the comment 11).

22. line 248: the wording "maximum duration" is misleading, since median is being presented

Response:

Many thanks for this remark. We replaced the term to the following.

Old sentence:

“For drought duration (Fig 4), the median duration of drought events overall the far future period (2070-2099) does not exceed 70 days, with the maximum duration of 70 days projected under RCP8.5 in Adige at Spondigna (Fig 4.a,f).”

New sentence:

“For drought duration (Fig 4), the median duration of drought events overall the far future period (2070-2099) does not exceed 70 days, with the highest median duration of 70 days projected under RCP8.5 in Adige at Spondigna (Fig 4.a,f).”

23. the "agreement" definition is not clear: is it about the magnitude of change (line 248) or just about the sign of change (line 258)?

Response:

The agreement on the sign of change among models is indicated in the figures (at least 90% agreement). As stated in the figures caption.

The sentence in line 248 was stating that more than 90% of the models projected an increase (positive sign) in drought duration up to 20-40% under RCP4.5. We improved the sentence to avoid misunderstandings

Old sentence (line248):

“More than 90% of the 13 model projections for this catchment agree on a potential increase in drought duration of 20-40% under RCP4.5, while RCP8.5 shows a slight decrease of 0-20% compared to the reference period (1989-2018).”

New paragraph

“More than 90% of the 13 model projections for this catchment agree on the sign of change in drought duration. Potential increases in drought duration up to 20-40% are projected under RCP4.5, while RCP8.5 shows a slight decrease up to 0-20% compared to the reference period (1989-2018).”

24. what about flipping the median change legend? it seems counter-intuitive to have the decrease upwards and vice-versa, though i understand it comes from more-water, less-water reasoning. Anyway, what does 100% decrease mean? can the Authors provide the formulas for these % changes in the Appendix and refer to them in the Methods?

Response:

Yes, exactly, the choice of colours and median change legend represents more-water/less-water reasoning. We changed the legend for the percentage change in all figures as the reviewer suggested. 100% decrease means that the median of the characteristic is zero which means no drought event. We modified the legend in all figures, and we set the lowest class of decrease as 80-100% (see figure below). We added the explanation of relative change calculation and model agreement in the supplementary information. Thank you for this suggestion.

Section 1 in the supplementary information:

“1. Changes in drought characteristics

Changes in drought characteristics are expressed as relative differences with respect to the reference period (1989-2018). Median values of each drought characteristic are first computed for each catchment, model, scenario (RCP4.5 and RCP8.5), and time period (reference, near-, mid-, and far-future). Relative changes for future periods are then calculated at the model level as the following equation (1).

$$\Delta X_{c,m,s,p} = \frac{\overline{X_{c,m,s,p}^{future}} - \overline{X_{c,m,s}^{ref}}}{\overline{X_{c,m,s}^{ref}}} \times 100 \dots (1)$$

Where \bar{X} denotes median drought characteristics and indices c, m, s, and p refer to catchment, model, scenario and period, respectively. For each catchment, scenario, and future period, projected changes are summarized using the median of the model-specific percentage changes. Model agreement is assessed based on the sign of change relative to the ensemble median: for each catchment, scenario, and period, the percentage of models with the same sign is computed. Agreement is classified as TRUE when at least 90% of models share the same sign, and FALSE otherwise.

The analysis is conducted (1) for all drought events combined and (2) separately by season.”

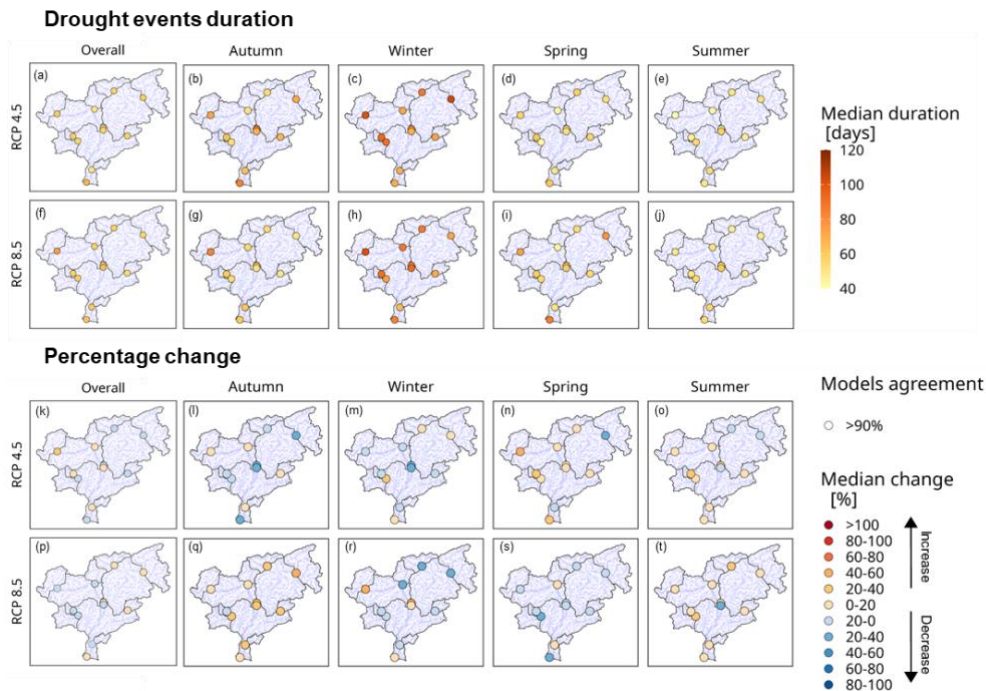


Figure 3: Drought event duration (a-j) and projected changes (k-t) under climate change for the RCP4.5 and RCP8.5 scenarios for far future (2070-2099). Median values are shown in colour. For percentage changes (k-t), agreement on the sign of change among models is indicated by black circles. Seasons are attributed according to the date of minimum flow.

25. lines 269-271: in two mid-elevation catchments (1500-2000) i expect that snow (or snowmelt) deficits play the main part, while T driven deficits contribute more marginally. the final sentence of line 271-272 (about elevation) is kind of hanging there. finally, minimum severity in winter droughts happens not only because of lower PET stress, but also because of very low absolute deviation from reference, as per my main comment.

Response:

Thank you for your comment. We agree with the reviewer and better clarify the concept also including comments suggested by the reviewer.

Old sentence:

“For drought severity (Fig 5), the largest total deficits are generally associated with drought events peaking in summer, particularly in Passirio at Merano and Isarco CDT under both scenarios, and in Rienza at Stegona under RCP4.5. This pattern likely reflects the combined effects of higher temperatures, increased evapotranspiration (Fig A3), and reduced snow contribution followed by rainfall deficits in spring and summer (Fig A4). These catchments are located at relatively high elevations (1500-2000 m). Drought severities are lower in autumn and spring, reaching their minimum in winter, reflecting higher precipitation and lower potential evapotranspiration (PET) during these periods.”

New sentence:

“For drought severity (Fig 4), the largest total deficits are generally associated with drought events with minimum flow in summer, particularly in *Passirio at Merano* and *Isarco CDT* (mid-elevation) under both scenarios, and in *Rienza at Stegona* (mid-elevation) under RCP4.5. This pattern likely reflects the combined effects of reduced snow accumulation and/or earlier snowmelt, which limit water availability during the warm season, together with rainfall deficits in spring and summer (Fig. A4). Higher temperatures and increased evapotranspiration (Fig. A3) may further exacerbate these deficits, although their role is secondary to snow-related processes. Drought severities are lower in autumn and spring and reach their minimum in winter. This seasonal pattern is consistent with the low-flow period, during which both streamflow and threshold levels are reduced, resulting in smaller deviations from the threshold and consequently lower cumulative deficits.”

26. lines 275-277 is true only if $T > 0$, which should be clarified.

Response:

Many thanks for your comment. We mentioned that this reduction in snow accumulation and shift towards rainfall during winter warming. Meaning during more warm winter (increasing temperatures). We improved the paragraph as following.

Old sentence:

“In contrast, total precipitation (Fig A4) shows a significant summer decrease only for the Fersina River basin, while winter precipitation increases up to 40% in high-elevation catchments, reflecting reduced snow accumulation and a shift toward rain during winter warming.”

New sentence:

“In contrast, total precipitation (Fig A4) shows a significant summer decrease only for the Fersina River basin, while winter precipitation increases up to 40% in high-elevation catchments, reflecting potential reduction of snow accumulation and a shift toward rain during winter warming (i.e. temperatures increase to $T > 0$ during winter)”

27. line 281: same as comment 25. Also, i see a potential issue here. If an event is attributed to spring due to peak occurrence, then even the whole severity of the event, likely happening in summer, is attributed to the spring season. The Authors should clarify this implication in their analysis.

Response:

Thank you for your feedback. Following what we already mentioned in comment 11, 25 and 26, yes, when a hydrological drought event has its minimum flow in spring however continues until summer, we attribute their occurrence to the spring season. Although this methodology is used in other studies, we have included results based on the date of maximum deficit in the supplementary information.

We keep however in the main manuscript the seasonal attribution of hydrological drought events according to date of minimum flow to keep consistency and comparability with other studies. (please check response to comment 11)

28. line 288-289: while useful to compare across different basins, % changes are very hard to relate to drought magnitude, which varies wildly across seasons. While debating absolute changes might be beyond the scope of the work, i encourage the Authors to stress this aspect: for this same reasons, % changes should be discussed within-season and not contrasting different seasons (or do it, with care).

Response:

Many thanks for your feedback.

We agree with the reviewer remark. The percentage of change in PET mentioned is relative to PET in the reference period of the same season. Increase in PET of up to 40% during winter means that the winter potential evapotranspiration sum is 40% higher than the winter potential evapotranspiration sum during the reference period (for given catchment, scenario and future period). The same apply for seasonal changes. We account for the reviewer suggestions by improving and better clarifying this concept.

Old sentence:

“Figure A3 supports this interpretation, showing that evapotranspiration increases by 20-30% under RCP8.5 throughout the year, with increases of up to 40% during winter across all catchments and in spring for the Noce and Adige-Nord basins.”

New sentence

“Figure A4 supports this interpretation, showing that annual potential evapotranspiration sum increases by up to 20-30% under RCP8.5 (Fig A4 z) relative to the reference period (Fig A4 f). At the seasonal scale, changes are computed relative to the corresponding season in the reference period, with increases reaching up to 30–40% in winter across all catchments (Fig A4 ab), and in spring for the Noce and Adige-Nord basins (Fig A4 ac).”

29. line 300: under RCP8.5 high warming is expected, again the attribution to winter and spring seems to point at the definition of peak drought, while i would expect the event to be more severe in the melt peak season (may-july)

Response:

Thank you for this comment. We agree with the reviewer point. We have made additional assessment using the date of maximum deficit as already mentioned in other comments. We present the results of the seasonal analysis with attributing drought events to the date of the maximum deficit in the supplementary information. And we keep the seasonal attribution according to date of the minimum flow to stay comparative with other studies (Please check figure S3 below). And YES, the increase in drought occurrence is up to 40-60% in summer under RCP8.5.

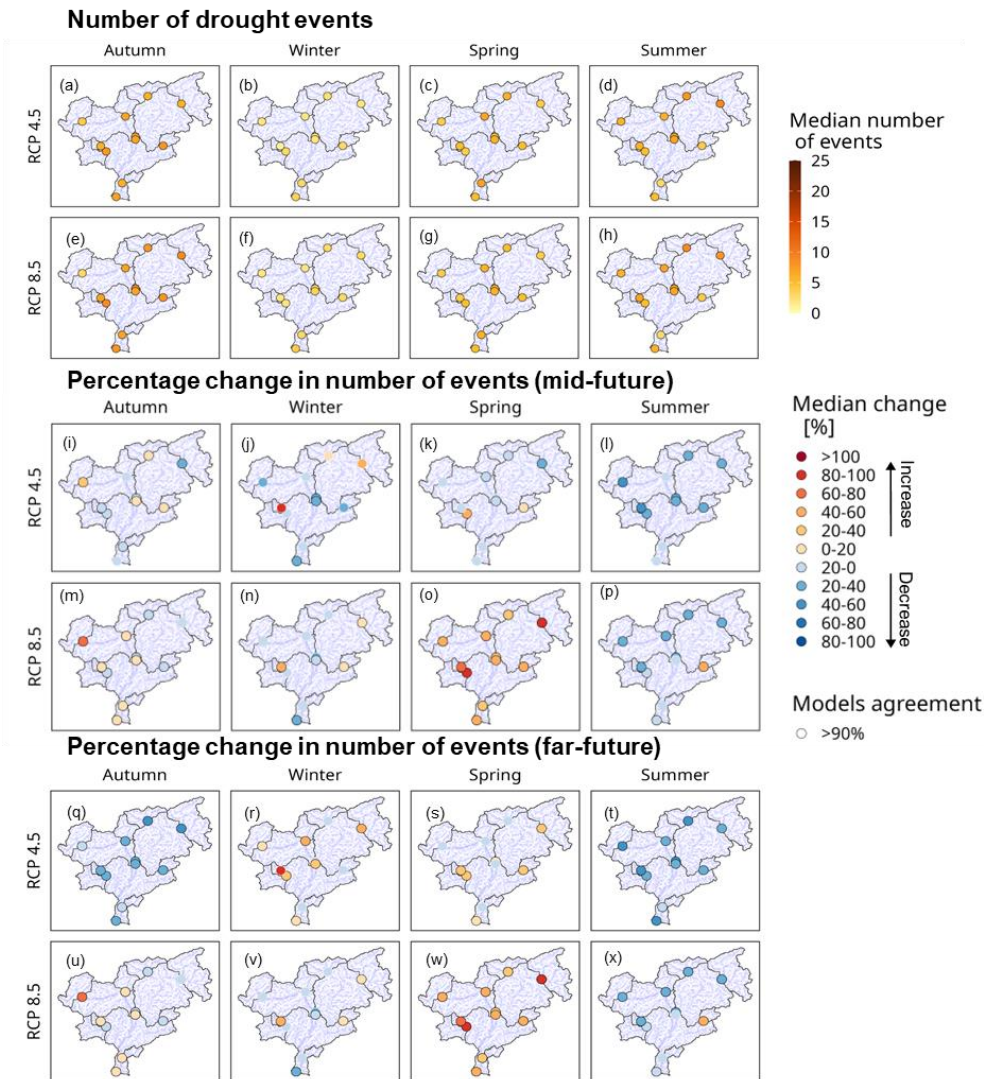


Figure S3: Number of drought events (a-j) and projected changes (k-t) under climate change for the RCP4.5 and RCP8.5 scenarios for mid future (2045-2074) and far future (2070-2099). Median values are shown in color. For percentage changes (k-t), agreement on the sign of change among models is indicated by black circles. Seasons are attributed according to the date of maximum deficit.

30. line 304+: why are the results for the mid future presented here? and only here?

Response:

Thank you for your comment. Results for the mid future were presented for the different characteristics (line 261+ for drought duration, line 293+ for drought severity, line 304+ for number of drought events, line 324+ for minimum flow).

31. line 311: i struggle to understand the definition of minimum flow used. The values are very low and I failed at converting them to m3/s meaningfully. can the Authors clarify the timestep related to these streamflow values, and any additional elaboration occurred to them? This also helps clarifying the comparison being done across catchments of very different size

Response:

Many thanks for your comment. As already mentioned in comment 10. The minimum flow and total deficit of each catchment were normalized by their contributing area in order to allow comparability between catchments (was mentioned in line 143-144).

Our motivation was to enable intercomparison of drought events among catchments, particularly along the river network and between nested catchments. For example, the minimum flow volume at the Villa Lagarina outlet (entire basin) cannot be directly comparable to that of the Fersina River, the Rienza River at the Stegona station, or the Isarco at Bolzano Sud catchment, due to their different contributing areas.

Therefore, to make results comparable across catchments, we normalized the total deficit and the minimum flow values by dividing their values by the contributing area of corresponding catchment, in the same way commonly applied in flood analysis. This procedure allows a consistent quantification of minimum flow and total deficit across basins of different sizes. A similar normalization approach has also been adopted in previous studies (Brunner, 2021).

32. lines 327-328 discuss drivers, though what have been presented so far are only metrics.

Response:

Thank you. This sentence was connection between what already have been presented. From the timing of drought events minimum flow and the analysis of the characteristics of the hydrological drought events across seasons we made assumptions on the drivers while showing the results (e.g. relating increased total deficit to potential lack of snow accumulation or rainfall deficit). In the section 4.3 the hydrometeorological drivers of hydrological drought events were assessed and illustrated to investigate what are the dominant drivers.

Old sentence:

“Overall, these results suggest that the nature and drivers of drought differ across RCP scenarios, leading to distinct drought characteristics depending on the season, elevation, and hydrological processes involved.”

New sentence:

“Overall, the results suggest that the nature and drivers of the hydrological drought events may differ across RCP scenarios, which lead to distinct drought characteristics depending on the season, elevation class, and hydrological processes involved.”

33. line 335: Maybe just my understanding,; the term "relative" would make me think of a piechart with all drought drivers. while the relative (spatial) importance is shown, Fig 8 only displays the dominant type.

Response:

Many thanks for your comment. We reformulated the sentence to the following.

Old sentence:

“Our results indicate that the relative importance of drought drivers varies across RCP scenarios, both in the reference and future periods.”

New sentence:

“Our results indicate that the dominant hydrological drought driver for each catchment vary spatially across RCP scenarios, both in the reference and future periods.”

34. line 353: nov-mar is perhaps the snow season? the Authors called it wet.

Response:

Yes, we corrected and made sure to keep the same term “snow season” in the manuscript consistent.

35. line 353-360 kind of goes over what each drought type means, without relating it to the results. I think this should either be paired with some results or be merged with what is already present in Section 3.1.2.

Response:

Thank you. We mentioned the difference of the different drivers between snowmelt drought and glacier melt drought and cold season drought to make it easier to follow the results. We removed this paragraph and we revised the sentence to the following:

Old sentence:

“These findings are consistent with the observed seasonal shift toward earlier drought occurrence and highlight the growing influence of temperature-driven processes in shaping future drought dynamics.”

New sentence:

“Our findings in figure 2, that indicate the seasonal shift of drought events’ minimum flow timing toward earlier occurrence (Fig 2), are consistent with both snowmelt driven drought (i.e. snow anomaly in precedent season) and cold snow season drought (i.e. low minimum flow in snow season due to prolonged temperatures below zero) and highlight the increasing influence of temperature-driven processes in shaping future drought dynamics.”

36. line 358+ again the concern that i raised in comment 16. I do not see an immediate link between drought occurrence and peak day as used here.

Response:

The old sentence in line 358 is as following:

Old sentence:

“Cold snow season droughts, in contrast, develop during the snow accumulation period, when temperatures remain below 0 °C and streamflow deficits coincide with snow accumulation instead of rainfall that would transform directly as runoff. These findings are consistent with the observed seasonal shift toward earlier drought occurrence and highlight the growing influence of temperature-driven processes in shaping future drought dynamics.”

New sentence:

“Our findings in figure 2, that indicate the seasonal shift of drought events’ minimum flow timing toward earlier occurrence (Fig 2), are consistent with both snowmelt driven drought (i.e. snow anomaly in precedent season) and cold snow season drought (i.e. low minimum flow in snow season due to prolonged temperatures below zero) and highlight the increasing influence of temperature-driven processes in shaping future drought dynamics.”

37. A general comment looking at figure 8 and at the decision tree is that, whenever there is no P deficit, most streamflow deficits will be redirected (peak..) towards nov-mar: together with $T < 0$, this makes me expect a great dominance of cold snow season droughts, though i would not be so sure all of them are.

Response:

Many thanks for your comment. Yes, a hydrological drought event is attributed to cold snow season drought in case of no approximate rainfall deficit, and the average temperatures below 0 (i.e. possible snow accumulation). This suggests that streamflow is below the Q20 potentially because of snow accumulation.

38. line 384: the second sentence is unclear to me/incomplete.

Response:

Many thanks for your comment. We corrected the sentence to the following.

Old sentence:

“Changes in seasonal drought duration vary depending on the RCP scenario. In spring-summer under RCP4.5 and autumn summer under RCP8.5. Similarly, Poschlod et al., (2025), found that summer low flow events are projected to extend towards longer event durations and to shift later in the year, i.e. May-November, in southern Germany.”

New sentence:

“Changes in seasonal drought duration vary depending on the RCP scenario. The highest increase (up to 20-40%) is projected in spring-summer under RCP4.5 and autumn-summer under RCP8.5. Similarly, Poschlod et al., (2025), found that summer low flow events are projected to extend towards longer event durations and to shift later in the year, i.e. May-November, in southern Germany.”

39. line 388-391: the relationship of streamflow drought trends with P trends in a snow-dominated area is not warranted, unless the catchment goes fully rain-dominated, hopefully not the case.

Response:

Many thanks for your comment. This sentence was discussing findings from other studies that project shifts in seasonal precipitation. This comment was made for the case where rainfall deficit was found the main driver of hydrological drought events (found in different catchments for different future periods as figure 8 shows). And at the same time, these findings can

explain the percentage changes in duration where we found no significant increase of hydrological duration (duration is projected to decrease in spring and winter up to 20-40% under RCP8.5).

Old sentence:

“In the same way, Zhu et al., (2025) and Kotlarski et al., (2023) also projects shifts, over mid-high latitudes (45N-75N), in the seasonal timing of extreme precipitation from summer into the colder seasons, spring and autumn, or even into winter, by the late 21st century which can also end/recovery of drought events due to extreme precipitation during this season.”

New sentence:

“In the same way, Zhu et al., (2025) and Kotlarski et al., (2023) also projects shifts, over mid-high latitudes (45N-75N), in the seasonal timing of extreme precipitation from summer into the colder seasons, spring and autumn, or even into winter, by the late 21st century which can also end/impede drought events due to extreme rainfall events during those seasons.”

40. lines 393-395 seem in contrast with 395-397, where the former state a decrease in summer-autumn deficit due to convective rainfall, while the latter state a negative correlation between temperature increase and precipitation change (i.e., P decrease?).

Response:

Old sentence:

“We show that rising temperatures and increased evapotranspiration intensify drought frequency and severity, while convective rainfall events may interrupt or temporarily break prolonged droughts in spring and summer. Kotlarski et al., (2023) similarly found that projected summer temperature increases are negatively correlated with precipitation changes, suggesting that rising mean temperatures may coincide with decreased mean precipitation in the Alps. Brönnimann et al., (2018) reported that extreme daily precipitation events in the Alps tend to become less frequent in late summer but more frequent in early summer and early autumn, coinciding with cooler conditions.”

We discuss here the increase in the severity of hydrological drought events that have minimum flow in winter and spring while at the same time the duration did not show increase (decrease in winter and spring up to 20-40% under RCP8.5). We here explain this by how the evapotranspiration and increase in temperature can increase drought frequency and severity (deficit from Q20), however, the increase of evapotranspiration can also increase the convective rainfall later which may lead to shorter drought events (since we found decrease in duration is projected under RCP8.5 in winter and spring and at the same time increase of severity). We cite then the findings of different studies, i.e. Kotlarski et al., (2023) that found increase in temperature and evapotranspiration in the Alps and Brönnimann et al., (2018) that found future projections showing shifts in rainfall events to early summer and early autumn.

We made some changes in the sentence to indicate more our point.

New sentence:

“We show that rising temperatures and increased evapotranspiration intensify drought frequency and severity, while convective rainfall events may interrupt or temporarily break prolonged droughts in spring and summer which may lead to shorter duration. Kotlarski et al., (2023) found that projected summer temperature increases are negatively correlated with

precipitation changes, suggesting that rising mean temperatures may coincide with decreased mean precipitation in the Alps. Brönnimann et al., (2018) reported that extreme daily precipitation events in the Alps tend to become less frequent in late summer but more frequent in early summer and early autumn, coinciding with cooler conditions.”

41. line 404-405 is true in RCP 4.5 but not in 8.5

We agree with the reviewer. We corrected the text.

Old sentence:

“Drought occurrence will significantly increase (more than 100%) compared to the reference period (1989-2018) in all seasons but mainly events having their peaks in summer, spring and winter.”

New sentence:

“Drought occurrence will significantly increase (more than 100%) compared to the reference period (1989-2018) in all seasons but mainly for the hydrological drought events having their peaks in summer, spring and winter under RCP4.5 and in autumn and summer under RCP8.5.”

FORMATTING (citations, typos): check lines 36, 52, 109-110, 120 (semi distributed?), 135,336 (snowmelt)

Response:

We thank you for the feedback. We have checked whole formatting and typos throughout the manuscript.

New inserted references:

APRIE, & PAT. (2022). *Provincial Environmental Energy Plan 2021-2030*.
https://www.provincia.tn.it/en/Administration/Documents/Provincial-Environmental-Energy-Plan-2021-2030#tempi_e_scadenze, last access: 12 May 2026.

Bouabdelli, S., Massari, C., Morlot, M., Castelli, M., & Formetta, G. (2025). High resolution (1 km-daily) potential evapotranspiration dataset over Europe and the Mediterranean region. *Journal of Hydrology*, 662, 133839.
<https://doi.org/10.1016/J.JHYDROL.2025.133839>

Brunner, M. I. (2021). Reservoir regulation affects droughts and floods at local and regional scales. *Environmental Research Letters*, 16(12), 124016. <https://doi.org/10.1088/1748-9326/ac36f6>

Brunner, M. I., Götte, J., Schlemper, C., & Van Loon, A. F. (2023). Hydrological Drought Generation Processes and Severity Are Changing in the Alps. *Geophysical Research Letters*, 50(2), e2022GL101776.
<https://doi.org/10.1029/2022GL101776;ISSUE:ISSUE:DOI>

Brunner, M. I., & Naveau, P. (2023). Spatial variability in Alpine reservoir regulation: Deriving reservoir operations from streamflow using generalized additive models. *Hydrology and Earth System Sciences*, 27(3), 673–687.
<https://doi.org/10.5194/HESS-27-673-2023>

- Brunner, M. I., Van Loon, A. F., & Stahl, K. (2022). *Moderate and Severe Hydrological Droughts in Europe Differ in Their Hydrometeorological Drivers*. *Water Resources Research*, 58(10), e2022WR032871. <https://doi.org/10.1029/2022WR032871;SUBPAGE:STRING:FULL>
- EURAC. (2026). *Produzione e consumo totale lordo di elettricità*. <https://www.eurac.edu/it/data-in-action/monitoraggio-del-piano-clima-alto-adige/produzione-e-consumo-totale-lordo-di-elettricit>, last access: 12 May 2026.
- Gaudard, L., Romerio, F., Dalla Valle, F., Gorret, R., Maran, S., Ravazzani, G., Stoffel, M., & Volonterio, M. (2014). *Climate change impacts on hydropower in the Swiss and Italian Alps*. *Science of The Total Environment*, 493, 1211–1221. <https://doi.org/10.1016/J.SCITOTENV.2013.10.012>
- Gesualdo, G. C., Benso, M. R., Mendiondo, E. M., & Brunner, M. I. (2024). *Spatially Compounding Drought Events in Brazil*. *Water Resources Research*, 60(11), e2023WR036629. <https://doi.org/10.1029/2023WR036629>
- Janzing, J., Wanders, N., van Tiel, M., & Brunner, M. I. (2026). *Spatiotemporal Dynamics of Streamflow Drought in the Larger Alpine Region*. *Water Resources Research*, 62(3). <https://doi.org/10.1029/2025WR040503>
- Majone, B., Villa, F., Deidda, R., & Bellin, A. (2016). *Impact of climate change and water use policies on hydropower potential in the south-eastern Alpine region*. *Science of The Total Environment*, 543, 965–980. <https://doi.org/10.1016/J.SCITOTENV.2015.05.009>
- Morlot, M., Rigon, R., & Formetta, G. (2024). *Hydrological digital twin model of a large anthropized italian alpine catchment: The Adige river basin*. *Journal of Hydrology*, 629, 130587. <https://doi.org/10.1016/J.JHYDROL.2023.130587>
- Napoli, A., Matiu, M., Laiti, L., Barbiero, R., Bellin, A., Zardi, D., & Majone, B. (2025). *Review on climate change impacts on the Water-Energy-Food-Ecosystems (WEFE) Nexus in the North-Eastern Italian Alps*. *Climatic Change* 2025 178:3, 178(3), 41-. <https://doi.org/10.1007/S10584-025-03890-Y>
- Van Loon, A. F., & Laaha, G. (2015). *Hydrological drought severity explained by climate and catchment characteristics*. *Journal of Hydrology*, 526, 3–14. <https://doi.org/10.1016/J.JHYDROL.2014.10.059>
- Vidal, J.-P., Martin, E., Kitova, N., Najac, J., & Soubeyroux, J.-M. (2012). *Hydrology and Earth System Sciences Evolution of spatio-temporal drought characteristics: validation, projections and effect of adaptation scenarios*. *Hydrol. Earth Syst. Sci*, 16, 2935–2955. <https://doi.org/10.5194/hess-16-2935-2012>
- Wanders, N., Wada, Y., & Lanen, H. A. J. Van. (2015). *Global hydrological droughts in the 21st century under a changing hydrological regime*. *Earth Syst. Dynam*, 6, 1–15. <https://doi.org/10.5194/esd-6-1-2015>