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

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Abstract

Drought is an increasingly important hazard in Alpine regions, where snow dynamics strongly influence river flow and support reservoir filling, irrigation, tourism, and ecosystem sustainability. Declining snow and warmer winters, which increase rainfall at the expense of snowfall, are shifting Alpine catchments toward lower-elevation hydrological regimes. This study examines shifts in drought seasonality and drivers in the Adige River basin under future climate conditions. Hydrological simulations for a reference period (1989-2018) and three future horizons (near 2020-2049, mid 2045-2074, and far 2070-2099) under climate scenarios are used to analyse drought drivers, timing, duration, severity, and intensity across catchments of different elevations. Results show that high-elevation catchments progressively shift from snowmelt- and glacier-driven droughts toward rainfall-deficit dominance. 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.

1. Introduction

Rivers in Alpine catchments are strongly influenced by elevation, snow accumulation, and glacier contributions, which shape the seasonal distribution of flow (Muelchi et al., 2021a; Van Loon, 2015). High-elevation catchments (>1500 m) typically exhibit a snowmelt-dominated regime, with high flows in late spring or early summer when snow and glacier melt peak, and low flows in winter or late summer once snow reserves are depleted. In contrast, lower-elevation catchments (<1500 m) display more rainfall-driven regimes, characterized by gradual seasonal variations and low flows primarily associated with rainfall deficits rather than snowmelt dynamics (Bruno et al., 2025; Muelchi et al., 2021a).

Climate warming is projected to reduce snowpack, accelerate snowmelt, and diminish glacier contributions across the Alpine region (Avanzi et al., 2024; Bozzoli et al., 2024). Projected warming of up to ~4 °C by the late 21st century may shift snow-

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driven runoff 1-3 months earlier (Coppola et al., 2021). Similarly, (Muelchi et al., 2021a) found that under RCP8.5, the seasonal flow regime in Alpine basins becomes increasingly rainfall-driven, with weaker spring and summer high flows due to reduced snowmelt and glacier contributions. Shifts from snowfall to rainfall further decrease both seasonal storage and mean streamflow, especially in snow-rich catchments, as demonstrated in global and regional analyses showing that declining snowfall fractions reduce annual runoff and alter the timing of streamflow (Berghuijs et al., 2014; Berghuijs and Hale, 2025; Han et al., 2024). Warming also amplifies evapotranspiration, further reducing water availability during warm summers and intensifying runoff deficits in snow- and glacier-fed catchments (Massari et al., 2022; Mastrotheodoros et al., 2020). Recent evidence from the Italian Alps shows that temperature anomalies strongly affected the snow drought during the extreme 2022-2023 event, and that glacier contributions to streamflow doubled to tripled compared to the 2011-2023 period, driven by an earlier start and longer duration of the glacier melt season (Leone et al., 2025). Over longer timescales, declining snow depth, particularly below 2000 m, has been linked to rising temperatures despite slight increases in winter precipitation (Bozzoli et al., 2024). Together, these studies indicate a fundamental shift toward earlier runoff peaks and a shrinking snow-ice buffer capacity of Alpine hydrology.

Droughts in Alpine basins are projected to become more frequent and intense, with notable shifts in their seasonal occurrence (Brunner et al., 2023; Haslinger and Blöschl, 2017). These changes often manifest as longer summer droughts, earlier spring onsets, or transitions toward autumn-winter drought conditions (Poschlod et al., 2025). In the Alps, (Brunner et al., 2019, 2022a) highlighted that drought severity and duration are particularly sensitive to snow and temperature anomalies, suggesting that warming-induced changes in snow dynamics will play a dominant role in shaping future drought behaviour. These changes have important implications for hydrological droughts in Alpine environments, where the interplay between snow, glacier, and rainfall processes governs the timing and severity of low flows (Brunner et al., 2022b). Past studies have identified multiple hydrological drought types, i.e. rainfall-deficit, snowmelt, glacier-melt, and cold snow season droughts, each with distinct physical mechanisms and seasonal patterns (Brunner and Tallaksen, 2019; Von Matt et al., 2024).

In the Alpine region, hydrological droughts basins can arise from distinct physical mechanisms (Brunner et al., 2022b). Rainfall-deficit droughts result from sustained precipitation shortages outside snow-controlled periods. Snowmelt droughts occur when winter snow storage is insufficient to sustain spring and early-summer runoff despite normal precipitation (Brunner et al., 2022b). Cold snow-season droughts develop during the snow-accumulation period, when temperatures remain below 0 °C and limited snowfall constrains streamflow. In catchments containing glaciers, glacier-melt droughts emerge during the melt season when reduced ice melt fails to compensate for low flows. These mechanisms vary across elevations and seasons, reflecting the interplay between temperature, snowfall, and meltwater contributions in Alpine hydrology (Brunner et al., 2022b). Yet, the spatial and elevational variability of these drivers, and how they may evolve under future climate scenarios, remain insufficiently understood, particularly at the catchment scale.

Snowmelt droughts are most common in summer, particularly in high-elevation catchments, where insufficient snow accumulation or accelerated melting leads to streamflow deficits outside the wet season (Brunner et al., 2019, 2022a). These findings emphasize that temperature and snow-related processes are central to drought formation and timing during the year (i.e. seasonality) , and that their evolution under continued warming will likely drive the transition from snow and glacier to rainfall dominated drought drivers.

To address these gaps, this study investigates the seasonality, characteristics, and dominant drivers of hydrological droughts in the Adige River basin, a representative Italian Alpine catchment spanning diverse elevations. Using multi-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) from the reference period (1989-2018) to the near-future (2020-2049), mid-future (2045-2074), and far-future (2070-2099).

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This study seeks to answer the following key questions:

- How will the seasonality of hydrological droughts changes across Alpine catchments under climate change?
- How will drought duration, occurrence, severity, and intensity evolve from the near to far future?
- Which processes (snowmelt, glacier melt, or rainfall deficits) will dominate future droughts, and how will these drivers vary with elevation?
- To what extent will changes in snow and glacier dynamics reshape Alpine drought characteristics in a warming climate?

By linking shifts in drought events timing to their underlying drivers, this work provides new insights into the evolving hydrological regimes of the Italian Alps under climate change.

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2. Data

2.1 Study area

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 region covers approximately 13,600 km², with elevations ranging from 63.5 meters to 3,636 meters above sea level (Fig 1.a). The first quartile elevation is 1,111 meters, and the third quartile is 2,082 meters, highlighting the region's predominantly mountainous character. The region plays a key role in agricultural production and hydropower generation. 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).

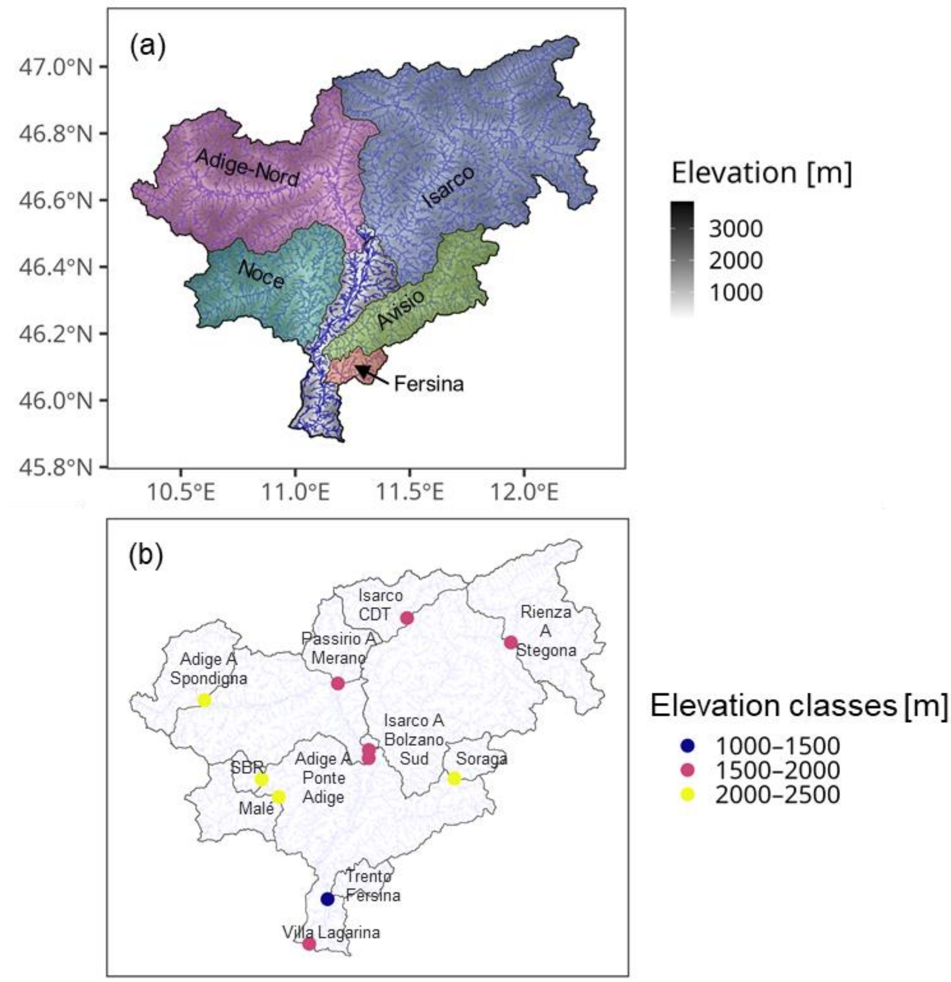

Figure 1. (a) Elevation model of the Adige River basin showing topographic variability and the major contributing catchments: Adige-Nord, Isarco, Noce, Avisio, and Fersina. Shaded colors represent catchment boundaries. (b) Elevation distribution of the 11 sub-catchment outlets used for the drought analysis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

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In this study, we focus on eleven natural catchments in the Adige River basin (Fig 1.b) following main streamflow gauges over major river subbasins within the Adige: Adige-Nord, Isarco, Noce, Avisio, Fersina, and whole Adige outlet southern at Villa Lagarina (Fig 1.a). Adige at Ponte Adige is the outlet of Adige-Nord River basin and Isarco A Bolzano Sud is the outlet of Isarco River basin. Adige at Villa Lagarina is downstream of all the Adige River, and the streamflow measured there represents the outlet of the entire basin. All 11 catchments are nested, meaning that each downstream level covers the entire contributing area of the upstream levels within that catchment. All streamflow gauges selected in this study correspond to natural, unregulated catchments, ensuring that these catchment flows are not influenced by hydropower reservoirs or other anthropogenic alterations (Table A1).

2.2 Baseline and future models

Thirteen GCM-RCM combinations (Table A2) from the Euro-CORDEX framework (Jacob et al., 2014) were obtained through the (CORDEX regional climate model data on single levels. Copernicus Climate Change Service (C3S) Climate Data Store (CDS)., 2025), providing daily temperature and precipitation data at ~12 km resolution for 1980-2005 and 2006-2100 under RCP4.5 and RCP8.5 scenarios. 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). The Bias-Corrected Climate Imprint (BCCI) method (Gebrechorkos et al., 2024) is used for the downscaling. It combines the Climate Imprint (CI) technique (Hunter and Meentemeyer, 2005) for spatial refinement with Quantile Delta Mapping (QDM; Cannon et al., 2015) for bias correction, preserving relative precipitation and absolute temperature changes.

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. The A-HDT hydrological model is an open access (https://github.com/geoframecomponents) semi distributed developed within the GEOframe framework by Formetta et al., (2014) and further expanded in Morlot et al., (2024).This model was forced with bias-corrected Euro-CORDEX rainfall and temperature inputs to generate the water cycle components for both the baseline and future periods.

Following Von Matt et al., (2024), the simulations were performed for four 30-year periods: baseline (1989-2018), near future (2020-2049), mid-future (2045-2074), and far future (2070-2099), during which drought events were identified and analysed.

3. Methods

3.1 Drought events

3.1.1 Drought identification

We define hydrological drought events using 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 calculated over a 30-year window for both historical and future periods, based on the assumption that water managers progressively adjust their strategies as the climate conditions change (Von Matt et al., 2024). To do so, we first smooth the daily time series over a time window of 30 days prior to compute the variable threshold to minimize the number of dependent events (Fleig et al., 2006). Then, we compute the drought threshold using the 20th flow percentile for each day of the year, derived within a moving window ±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 drought threshold. 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. In this study, we keep the threshold of 20th percentile which was

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set in different European and high elevation catchments drought analysis studies (Brunner et al., 2022a; Van Loon and Laaha, 2015).

The duration in days is the number of the consecutive days during which the smoothed streamflow series was below the drought threshold. The number of events is the number of 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 over the area of the basin (Brunner and Stahl, 2023; Gesualdo et al., 2024b). The intensity, is defined as the minimum flow, in mm, during the drought event and the highest intensity refer to the smallest values normalised by catchment area (Brunner and Stahl, 2023; Gesualdo et al., 2024b).

Drought event seasonality describes the time when drought events are most likely to occur during the year. Following Muelchi 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 drought peak timing) 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) (Muelchi 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 intensity may shift under future conditions.

3.1.2 Hydrological drought classification

We applied a standardized drought classification scheme that distinguishes eight hydrological drought types based on their dominant drivers and seasonal context (Brunner et al., 2022b; Van Loon, 2015; Van Loon and Van Lanen, 2012). In a first step, drought events identified in Section 2.21 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.

4. Results

In this study, we analyse shifts in the seasonality of drought events across the reference (1989-2018), near-(2020-2049), mid-(2045-2074), and far-(2070-2099) future periods under two emission scenarios (RCP4.5 and RCP8.5). We first assess changes in the distribution of drought peak timing to identify shifts in dominant drought months. Next, we investigate how the dominant

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drought drivers evolve across scenarios and time periods. Finally, we examine seasonal variations in the number of drought events, their duration, severity, and minimum flow under all RCP scenarios and compare their change with change in precipitation and evapotranspiration for the far-future period, while corresponding results for the mid-future period are provided in the Appendix (Fig A2 to A5).

4.1 Seasonal Shifts in Drought Peaks timing

We analysed the probability distribution of drought event peak timing to assess shifts in the occurrence of drought peaks. Results are shown in Figure 2 for representative catchments across different elevation bands: Malé (2000-2500 m), Isarco a Campo di Trens (1500-2000 m), Fersina (1000-1084 m), and at the outlet of the Adige River (Villa Lagarina). 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.

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.

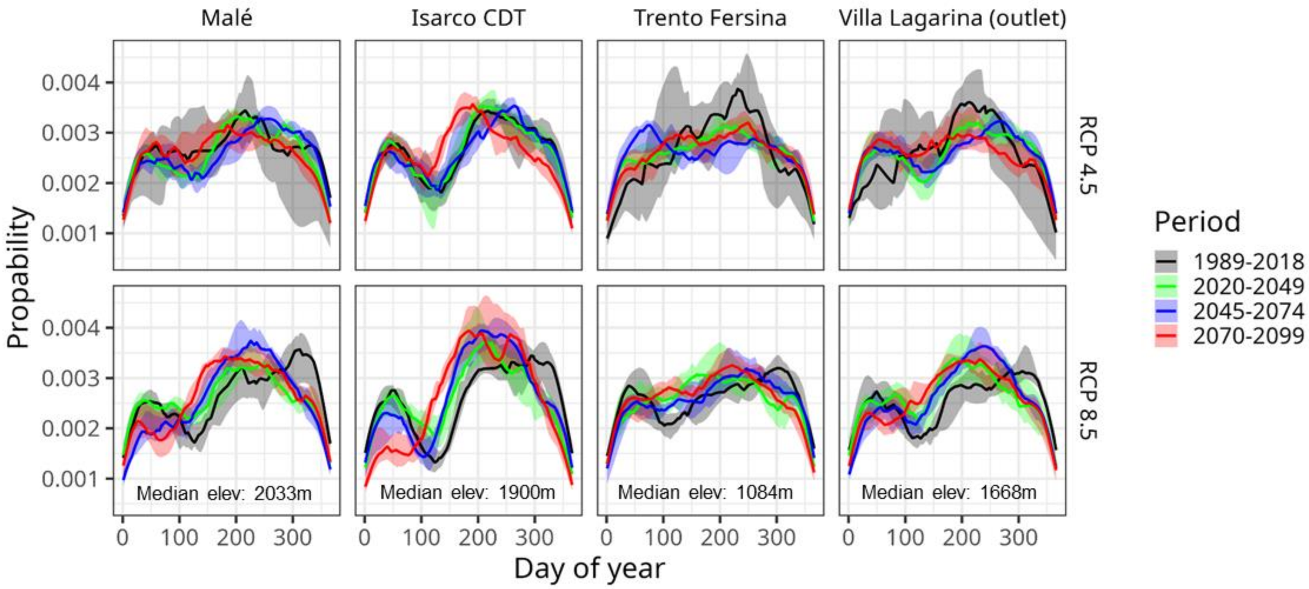

Figure 2: Seasonality of drought peak timing. Shaded areas show the probability density of drought events across all 13 models for each catchment, with medians indicated. Solid lines represent the median across all models. Results are shown for RCP4.5 and RCP8.5 across all periods: reference period (1989 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.

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Under RCP4.5 (Fig 2.a-d), the timing of drought peaks in future periods remains broadly similar to the reference period, with the highest densities occurring from May to October. Drought peak timing in the near- and mid-future periods is generally consistent with the reference, except for the Fersina basin (1000-1500 m), where drought density gradually increases over a single extended peak from February to October across all future periods, while in the mid-future the peak is more concentrated in spring (Fig 2.c). The reference period shows higher drought density in summer (August-September), whereas in the near- and far-future periods peaks shift earlier to June-July, especially for the far future (Fig 2.a.b). At lower elevations (Fersina and the outlet), models also project an increase in drought probability in spring (February-mid-April) across all future periods (Fig 2.c.d).

Under RCP8.5 (Fig 2.e-h), drought peaks consistently shift earlier in summer (Apr-July), especially in the far future, whereas the reference period shows a later maximum in late October, likely reflecting prolonged events extending from summer due to rainfall deficits. In the far-future RCP8.5 period, a single dominant summer peak (July-September) emerges across both high-elevation catchments and the outlet. In the Fersina basin, drought density does not decrease after the spring peak, suggesting persistent rainfall-driven drought events (Fig 2.g).

These findings suggest that flow regimes in high-elevation catchments will likely shift toward earlier summer droughts dominated by snowmelt and rainfall deficits, whereas lower-elevation catchments will likely become increasingly controlled by rainfall-driven droughts.

Consistent with previous results, the timing of higher drought probability density was analyzed across months. Figure 3 shows the months with the highest probability of drought peak timing (the mode) for each catchment in the Adige basin, for both scenarios and all time periods.

Under RCP4.5, drought peaks in the reference period occur mainly between July and September (Fig 3.a). In the near and mid future periods, these peaks are projected to shift earlier, predominantly to April-May, and even to February in some upstream catchments such as Avisio at Soraga, Fersina (near future), and San Bernardo Rabi (mid future) (Fig 3.b.c). These shifts likely reflect earlier snowmelt and reduced snow contribution. In the far future, the highest drought probabilities occur between April and July (Fig 3.d), suggesting the combined influence of spring and summer warming and prolonged rainfall deficits extending from spring.

Under RCP8.5, drought peaks in the reference period (Fig 3.e) are most frequent in March-April for the western upstream catchments (upstream Adige Nord, Noce) and at the outlets of Adige Nord and Isarco, in June for Passirio at Merano, and in July for Avisio at Soraga and Isarco CDT. At the outlet of the Adige, drought peaks occur more often in April (Fig 3.e). In the near future (Fig 3.f), peaks shift to June-August in most high elevation catchments, except for Adige at Spondigna, the highest elevation catchment, which retains a March peak, and Avisio at Soraga, where peaks occur in April. At the outlet of the Adige, drought peaks are also projected to shift to June.

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In the mid future period (Fig 3.g), drought peaks in the Noce (Malé and San Bernardo Rabi) and Avisio at Soraga catchments are projected to shift to October, indicating an increased likelihood of drought occurrence in late summer. At the outlet, peaks occur in April, likely reflecting more severe spring droughts, consistent with patterns in Adige Nord and Isarco CDT. In the far future (Fig 3.h), drought peaks are projected to occur mainly in April across the entire Isarco River and in Passirio at Merano, in September for the Noce, in August for Avisio at Soraga and Fersina, and in December at the outlet.

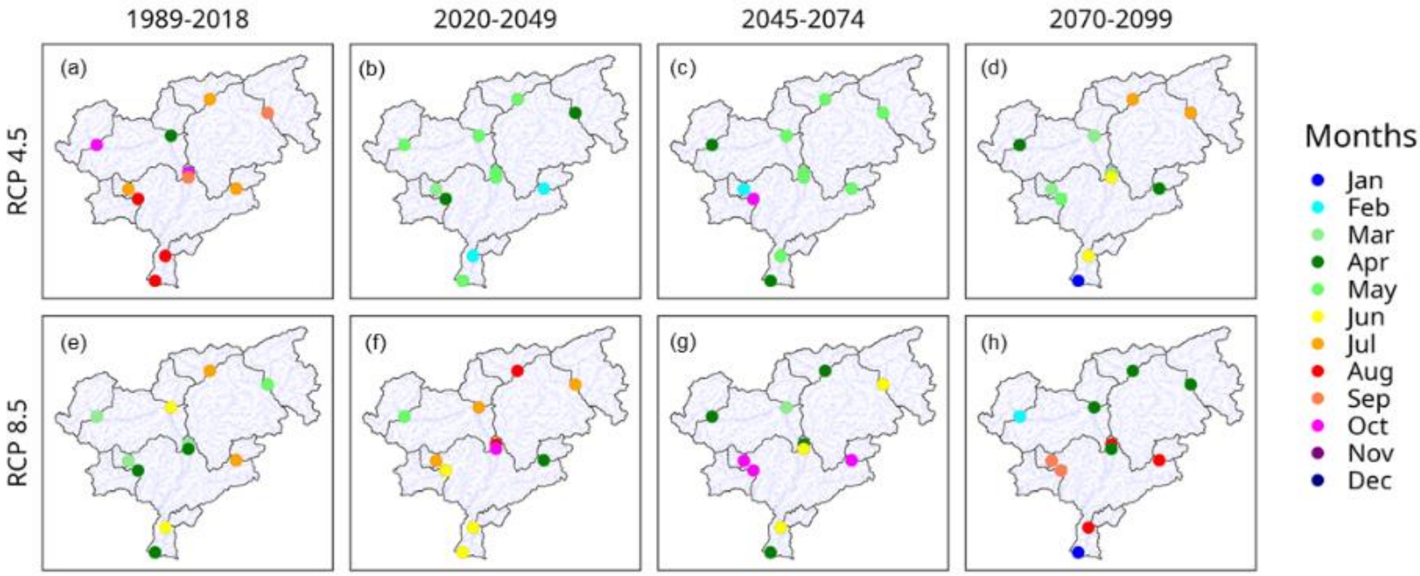

Figure 3: Spatial distribution of drought peak timing across Adige basin catchments under RCP4.5 and RCP8.5 for the reference period (1989-2018) and future periods: near future (2020-2049), mid future (2045-2074), and far future (2070-2099).

High elevation catchments generally exhibit spring drought peaks, highlighting their dependence on snowmelt, whereas lower elevation catchments show a more mixed pattern, with drought peaks extending into early autumn.

4.2 Changes in drought characteristics under RCP future scenarios

Given the projected changes in drought seasonality, the characteristics of future drought events are assessed both seasonally, across the four seasons, and over the entire period. In this section, we analyze these characteristics under the two emission scenarios, RCP4.5 and RCP8.5. We consider the median values and their relative changes in the far future for four key indicators: drought duration, total deficit, minimum flow, and number of drought events, as shown in Figures 4 to 7.

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). 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). Considering the seasonal distribution, drought duration is longest for drought events having their peaks during winter for both scenarios (exceeding 100 days), in autumn under RCP4.5, and in spring under RCP8.5. Duration is shorter than 40 days in most catchments for events having their peaks during spring and summer under RCP4.5, and during summer and autumn under RCP8.5.

Changes in seasonal drought duration for the far future vary depending on the RCP scenario. Under RCP4.5, the increase in drought duration is more pronounced in spring and summer, with values reaching 20-40% across most of the Adige catchment except for the Isarco in summer (*Rienza a Stegona* and *Isarco CDT*). This suggests that spring drought events will likely extend

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under this scenario. Under RCP8.5, drought duration increases are strongest in autumn, with projected changes reaching 40-60% and summer (20-40%). More than 90% of the models agree on the sign of change across all catchments and throughout all seasons. However, the projected decrease in drought duration for the Fersina River is not significant across all models over the entire period (Fig 4p). At the seasonal scale, projections show a slight decrease of 0-20% only in winter, while drought duration increases in the other seasons. For the mid-future period (2045-2074), drought duration increases under RCP4.5, particularly in spring and summer (Fig A2). In spring, increases reach 60-80% in the *Isarco CDT* and at the Adige outlet, and up to 80-100% at the Adige-Nord outlet. In summer, increases of 60-80% are projected for the *Adige at Spondigna*. Under RCP8.5, the strongest increases occur in autumn (40-60%) across the entire basin.

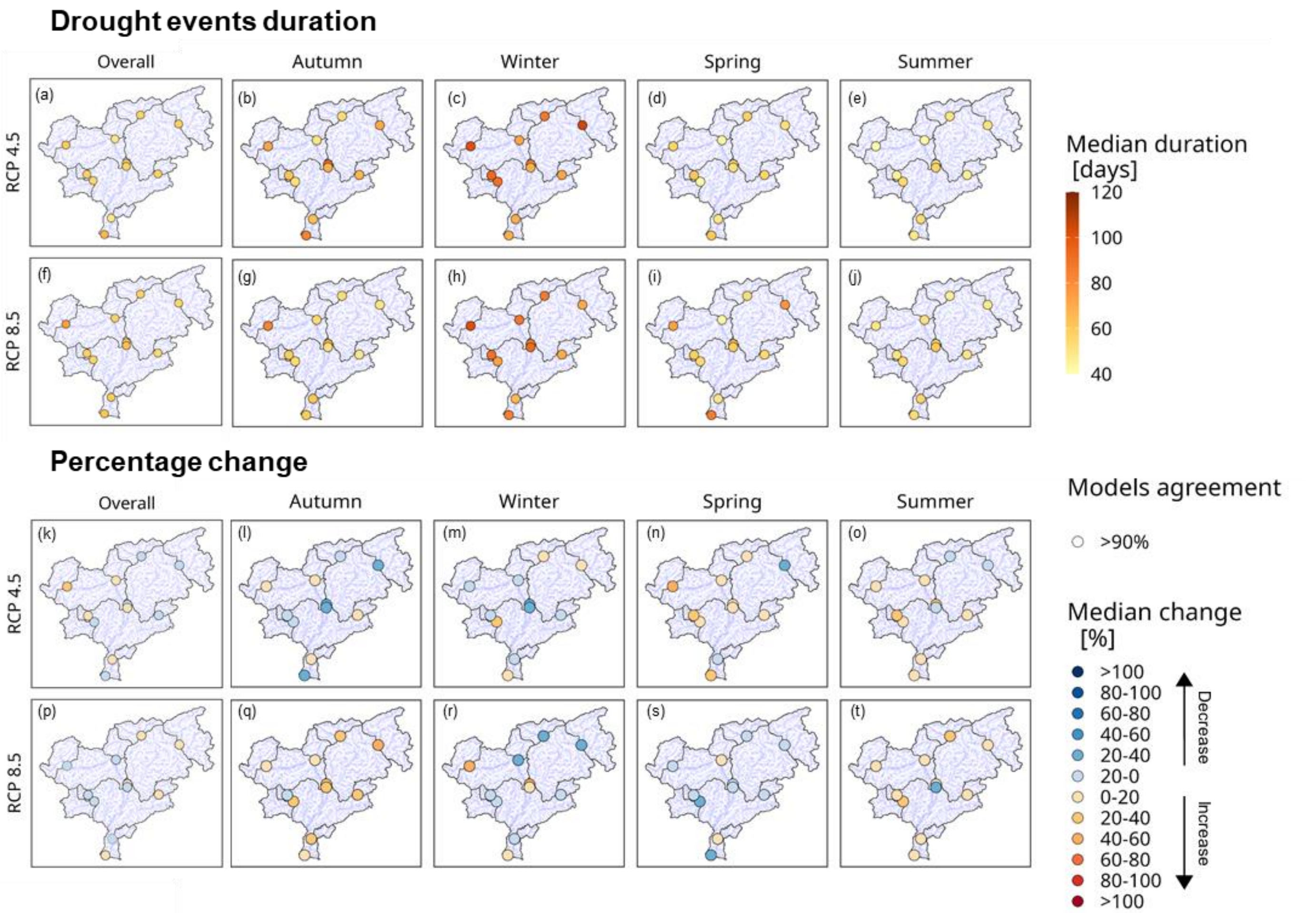

Figure 4: Drought event duration (a-j) and projected changes (k-t) under climate change for the RCP4.5 and RCP8.5 scenarios for far future (2070-2099). Median values are shown in colour. For percentage changes (k-t), agreement on the sign of change among models is indicated by black circles

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

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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.

For the far future, projections show an increase in PET sum of 20-30% throughout the year, up to 40% under RCP8.5, and 10-20% across all basins in winter and spring under RCP4.5 (Fig A3). 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.

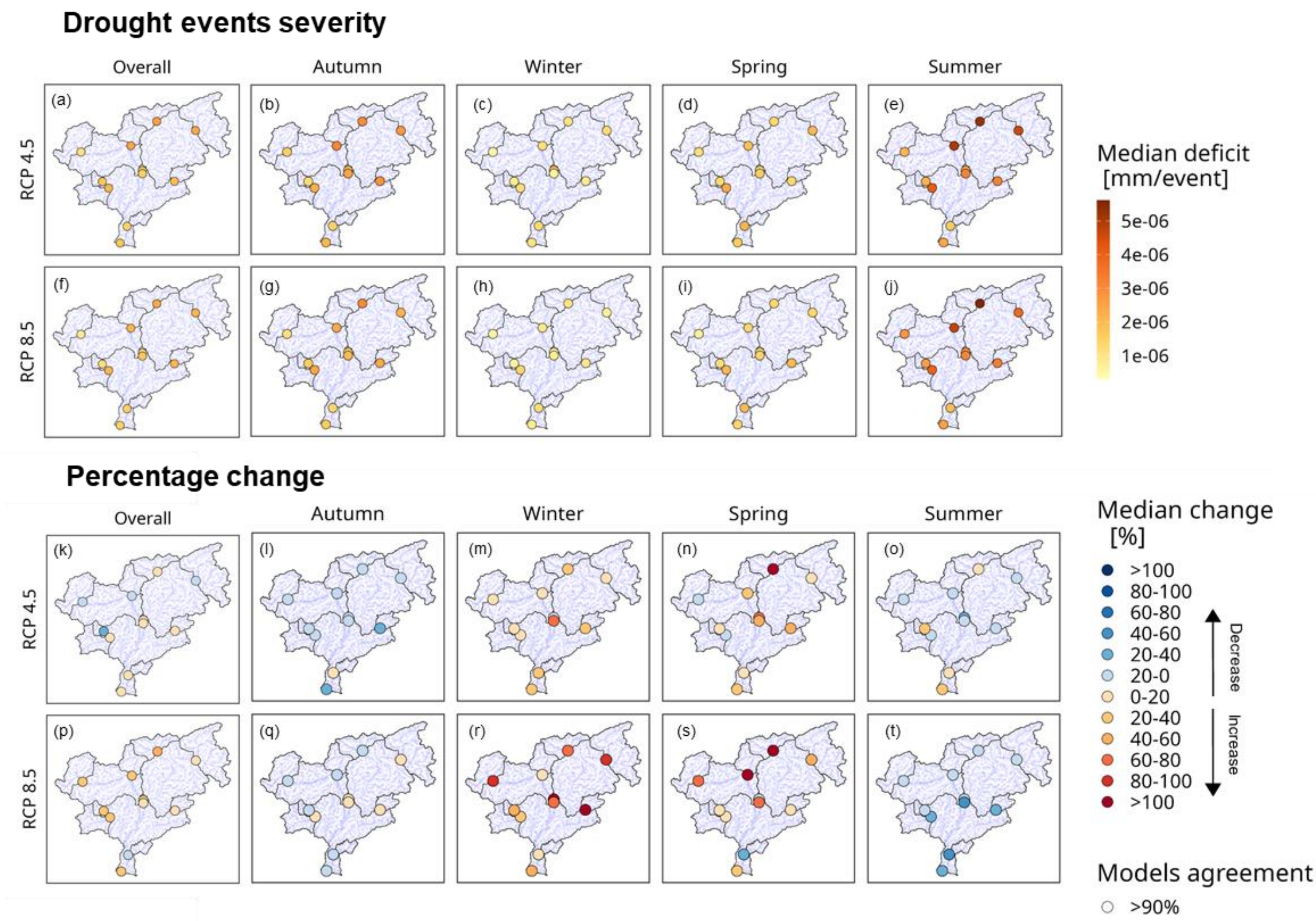

Figure 5: Drought event severity (a-j) and projected changes (k-t) under climate change for the RCP4.5 and RCP8.5 scenarios for far future (2070-2099). Median values are shown in colour. For percentage changes (k-t), agreement on the sign of change among models is indicated by black circles.

For drought severity changes, the largest increases (exceeding 100%) are projected for events peaking in winter and spring. This indicates that, although drought duration does not increase substantially during these seasons, the total deficit rises significantly, suggesting that drought events may become slightly shorter but more intense. In contrast, deficits are projected to decrease in summer, by up to 60% in low-elevation catchments, and in autumn, particularly at high elevations. This pattern

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likely reflects the interplay between rising temperatures and increased evapotranspiration, which intensify drought severity, and convective rainfall events, which may interrupt or temporarily alleviate prolonged droughts in spring and summer, contributing to the reduced summer-autumn deficits. 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.

Over the entire period (Fig 5.k.p), drought severity is projected to increase by 0-20% under RCP4.5 in the southern Adige, including Malé, Soraga, Fersina sub-catchments, the outlet of Isarco and Adige-Nord, and at the outlet. Under RCP8.5, increases are projected across all sub-catchments and at the 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 A5). Under RCP8.5, the total deficit exceeds 100% of increase at the *Isarco outlet* and *Soraga* in winter, and in *Isarco CDT* and *Passirio at Merano* during spring.

For drought occurrence (Fig 6), the number of drought events in the far future is projected to increase across the entire Adige basin. Under RCP4.5, up to 24 events are projected in Isarco CDT and Avisio at Soraga, and around 10 events in the other catchments, including the outlet. Under RCP8.5, at least 20 drought events are projected across all catchments, including the outlet. Seasonally, up to six events are expected in winter, summer, and autumn under RCP4.5, with Isarco CDT and Avisio at Soraga showing the highest number of events. Under RCP8.5, droughts occur more frequently in winter and spring, reaching up to nine events. All scenarios indicate an increase, exceeding 100% in some catchments, in the number of drought events across the basin. The increase is strongest under RCP4.5, particularly in the western part of the basin and for droughts peaking in summer. Under RCP8.5, drought occurrence increases mainly in autumn, affecting the entire basin, with the largest rises in Adige Nord and Isarco. For the mid-future period (2045-2074), the number of drought events under RCP4.5 shows a marked increase over the entire period, with the strongest rises occurring in winter and summer (exceeding 100%) (Fig A6). Under RCP8.5, drought frequency is also projected to increase, particularly in autumn, affecting all catchments.

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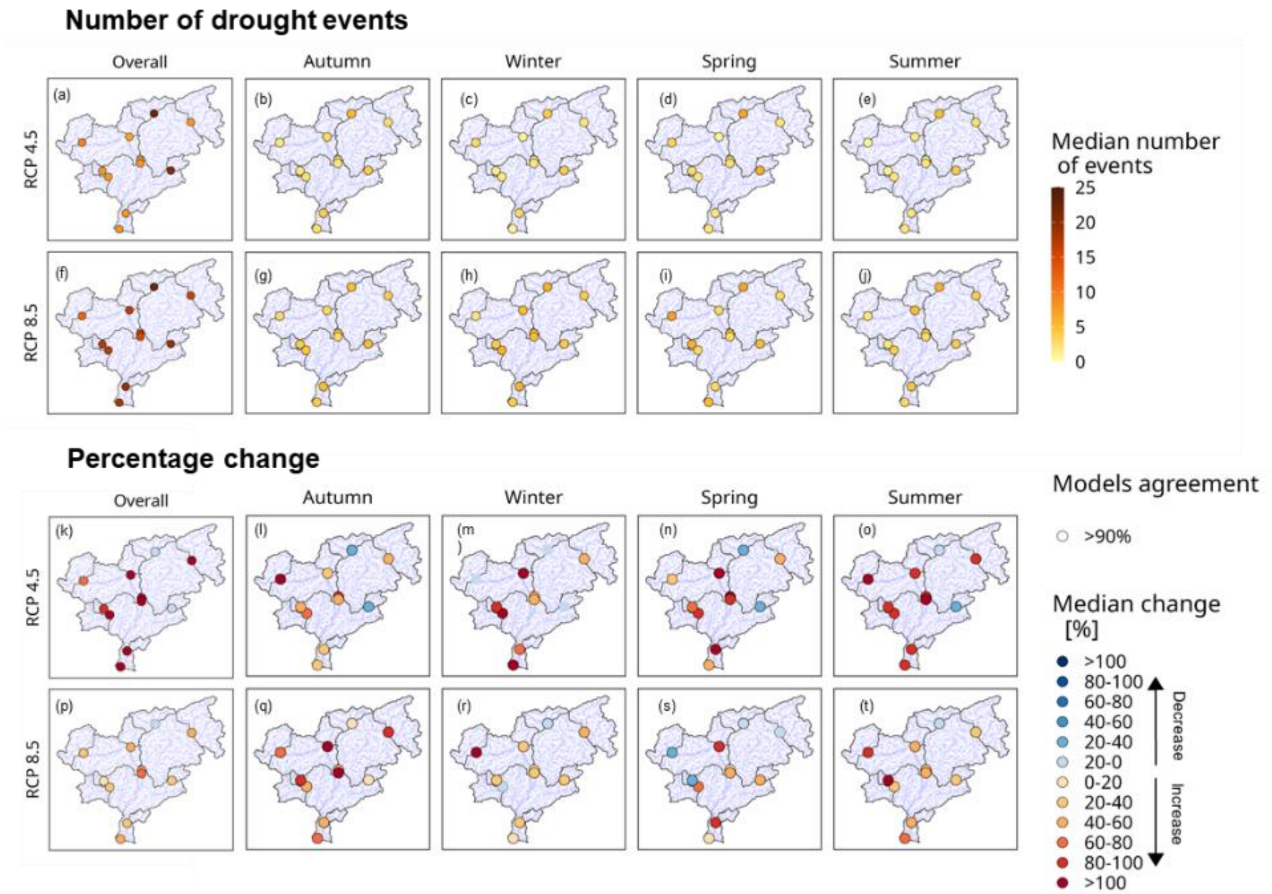

Figure 6: Number of drought events (a-j) and projected changes (k-t) under climate change for the RCP4.5 and RCP8.5 scenarios for far future (2070-2099). Median values are shown in color. For percentage changes (k-t), agreement on the sign of change among models is indicated by black circles.

For minimum flow (Fig 7), the lowest values are projected mainly in the Fersina River and San Bernardo Rabi throughout the far-future period under both RCP4.5 and RCP8.5. Seasonally, minimum flows are lowest in winter and spring for both scenarios, with particularly low values projected in Fersina, Passirio at Merano, and San Bernardo Rabi during winter drought events. Minimum flows are slightly higher in autumn and highest in summer, except in the Fersina River, which consistently shows the lowest projected values among all catchments. This pattern likely reflects the limited snow contribution in this low-elevation catchment (1000-1500m), which reduces its ability to sustain baseflow compared to snow-fed systems in high-elevation catchments. At the outlet, the lowest minimum flows occur during droughts peaking in winter and spring.

Decreases of up to 60% are projected in autumn and summer, particularly under RCP8.5. By contrast, increases in minimum flow are projected for drought events peaking in spring under almost all scenarios, especially in higher-elevation catchments where earlier snowmelt and glacier melt are dominant drivers and warmer winter and spring increase the precipitation (Fig A4). Over the full period, minimum flow decreases by about 20-40% across most of the basin. However, at the Adige outlet, increases in minimum flow are projected under specific conditions: for winter events under RCP4.5, for spring events under

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RCP8.5. In these cases, the increase relative to the past period may be explained by enhanced snowmelt in spring and a shift from snowfall to rainfall in winter (Fig A4), both of which alter the seasonal behavior of Alpine rivers. For the mid-future period (2045-2074), the minimum flow shows a strong increase in spring (exceeding 100%) in high-elevation catchments such as Isarco CDT, Passirio at Merano, and Male (Fig A7). In contrast, decreases are projected in both autumn and summer, particularly at lower elevations in autumn.

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.

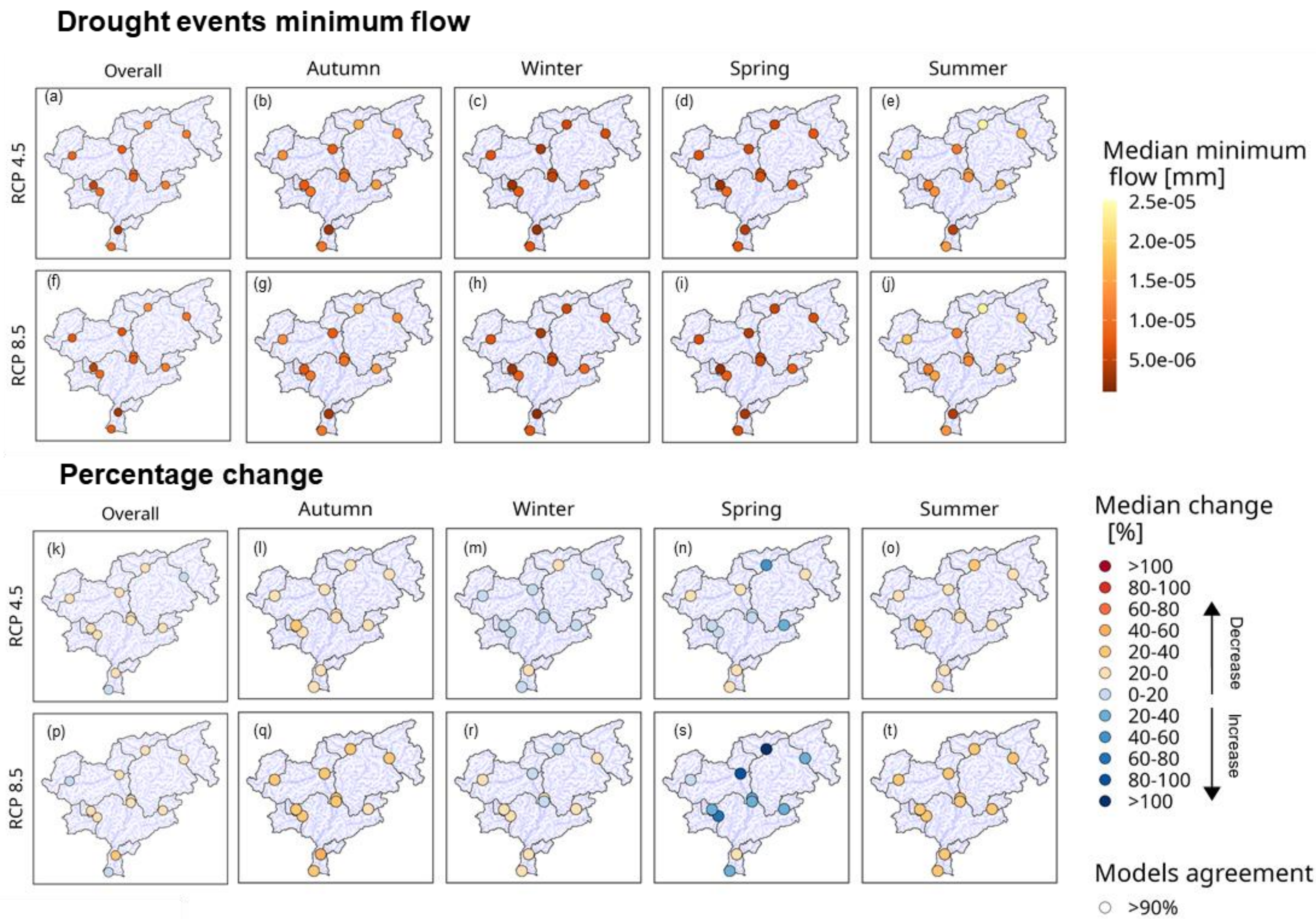

Figure 7: Drought events minimum flow (a-j) and projected changes (k-t) under climate change for the RCP4.5 and RCP8.5 scenarios for far future (2070-2099). Median values are shown in color. For percentage changes (k-t), agreement on the sign of change among models is indicated by black circles.

4.3 Shifts in drought drivers

Drought drivers were identified for each drought event across all study periods, and the dominant drivers are shown in Figure 8. Our results indicate that the relative importance of drought drivers varies across RCP scenarios, both in the reference and

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future periods. Overall, rainfall deficits, snowmel, glacier melt, and cold snow season droughts emerge as the dominant drivers. During the reference period, glacier-melt is identified as the dominant driver for Adige at Spondigna, whereas snowmelt dominates in Rienza at Stegona under RCP4.5. All other catchments are primarily affected by cold snow season droughts, except the outlets of Adige-Nord and the outlet of entire Adige (at Villa Lagarina), where rainfall deficit dominates. Under RCP8.5, nearly all drought events are driven by cold snow season droughts, except in the Fersina River, where snowmelt is the dominant driver.

In the near future, droughts are mainly driven by cold snow season processes under RCP4.5, and by rainfall deficits under RCP8.5. In the mid-future, under RCP4.5, droughts in the upstream Adige-Nord and Rienza at Stegona are primarily associated with cold snow season droughts and snowmelt (at the outlet of Adige-Nord), while rainfall deficits dominate in the other catchments. Under RCP8.5, snowmelt droughts become dominant across most catchments during the mid-future period, except for the upstream Adige-Nord and Isarco CDT, where cold snow season droughts remain prevalent. In the far future, droughts are mainly driven by rainfall deficits and cold snow season droughts under both scenarios, while warm snow season droughts become dominant in the Fersina River, likely reflecting higher winter temperatures. snowmelt droughts continue to dominate in Rienza at Stegona throughout the far future.

Overall, rainfall deficits emerge as the dominant driver in the near future under RCP8.5 and in the mid-future under RCP4.5, whereas temperature- and snow-driven processes (snowmelt and cold snow season) dominate high-elevation catchments, particularly in the mid- and far-future under RCP8.5.

Snowmelt droughts are defined here as runoff deficits occurring outside the wet season (November-March) without concurrent or preceding rainfall deficits, associated with anomalies in snow water equivalent (SWE). These deficits develop outside the snow season when insufficient SWE remains to sustain meltwater contributions. Glacier-melt droughts occur during the glacier-melt season (July-September) in catchments containing glaciers, also without concurrent rainfall deficits. 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.

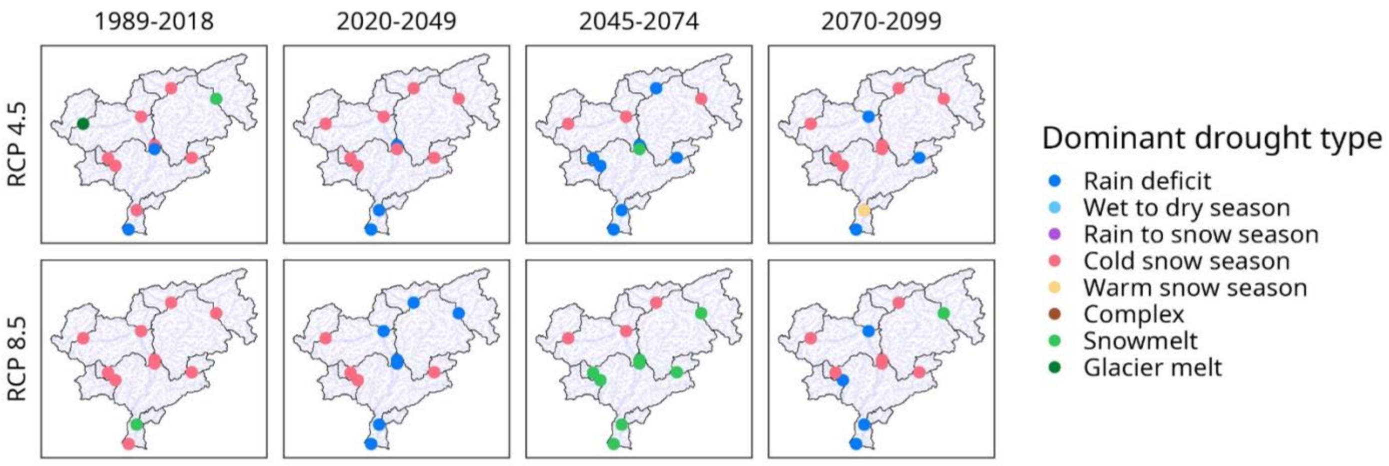

Figure 8: Dominant drought drivers under climate change for the RCP4.5 and RCP8.5 scenarios.

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5. Discussions

Drought peaks in the Adige cluster into two main periods: a spring peak (February-mid-April) and a summer peak (May-September), with differences across scenarios expressed primarily in timing. The transition between these two periods reflects hydrological recovery linked to high flow season with snowmelt and spring rainfall. Comparable seasonal patterns were also identified in southern Switzerland. Von Matt et al., (2024) reported that compound drought events there tend to concentrate in two windows: one spanning January to mid-April, with probabilities peaking around February, and another extending from mid-summer into late autumn. Similarly, (Muelchi et al., 2021b) found that the southern Alpine catchment of Verzasca-Lavertezzo in southern Switzerland exhibits a two-peaked runoff regime, with one peak in late spring and another in autumn. This bimodal regime was found persisting in future projections, though the spring and summer peaks become weaker under RCP8.5 due to enhanced winter runoff and reductions in spring (-0.2 to -1.9 $mm.d^{-1}$) and summer (-1.4 to -1.7 $mm.d^{-1}$) discharge (Muelchi et al., 2021b).

Scenario-specific differences become most pronounced in summer. Under RCP4.5 and RCP8.5, summer drought peaks shift to earlier months. These shifts suggest that streamflow dynamics in high-elevation catchments may increasingly resemble those of lower elevations, while low-elevation catchments transition toward droughts more directly driven by rainfall deficits. Von Matt et al., (2024) similarly projected that in southern Switzerland compound drought events during July-October will increase, with concurrent droughts shifting to earlier in summer. (Muelchi et al., 2021b) also reported that Alpine catchments are expected to experience a shift in seasonal flow regimes, with annual high flows occurring earlier in the year due to the reduced role of snowmelt and glacier-melt in sustaining summer discharge. As a result, winter half-year flows are projected to intensify, while summer high flows weaken. This redistribution of flow seasonality aligns with our finding of earlier summer drought peaks and highlights the increasing dominance of rainfall-driven processes. Together with previous studies (Brunner et al., 2021, 2022a; Muelchi et al., 2021a, 2021b), this supports the interpretation that Alpine catchments are transitioning toward lower elevation-like hydrological behaviour under climate change.

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. Wang et al., (2025) found the main drought seasons exhibit a transition trend from spring-winter to summer-autumn over time and this transition trend becomes increasingly evident as the emission level increases in China. 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.

The projected increase in drought severity, particularly for events peaking in winter and spring, points to a shift toward more severe, but not necessarily longer, droughts. The decrease in deficit in summer and autumn can be explained by the same processes. 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. This shift in seasonality was linked to summer drying, with stronger signals in models showing decreases in annual or summer mean precipitation. Our findings of larger severities under higher-emission scenarios are consistent with previous studies projecting more severe droughts under climate change (Spinoni

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et al., 2018; Sutanto et al., 2025). Similar results were reported by Ghazi et al., (2025) in Poland, where drought severity is also expected to intensify under future scenarios.

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. (Sutanto et al., 2025) also found similar results by studying compound and cascading drought and heatwave events in the Alpine region, they found that the number of compound events is expected to increase sharply (from 4 events in the past to 35 events in the future). They also expect that some parts of France, the Alps, southern Germany, and Moldova will become new hotspot regions for compound and cascading dry hazards. Ghazi et al., (2025) found notable increase in Poland for both hydrological and agricultural droughts.

Changes in minimum flow are closely linked to the dominant drought drivers. Increases in minimum flow, particularly at higher-elevation catchments during winter and spring, reflect the influence of earlier snowmelt. By contrast, decreases in minimum flow are more likely associated with rainfall-driven events or with severe snow droughts, where insufficient winter snowpack results in reduced flows during the subsequent spring and summer. Consistent with our findings, Coppola et al., (2021) found that projected warming of up to ~4 °C in the Alps by the late 21st century is expected to anticipate snow driven runoff timing by 1-3 months.

Our findings are consistent with the broader European patterns described by (Brunner et al., 2022a), who showed that rainfall-deficit droughts dominate in Western Europe from fall to spring, while cold snow season droughts prevail in Eastern and Northern Europe during the same period. In the Alps, snowmelt droughts dominate in summer, particularly in high-elevation catchments, with severe droughts often emerging as wet-to-dry season transitions. Similarly, in the Adige basin, we find that rainfall-deficit, and cold snow season droughts emerge as the most important drivers, with snowmelt and glacier-melt droughts shaping drought occurrence in high-elevation catchments.

Recent evidence from the Italian Alps indicates that the 2022-2023 snow drought substantially enhanced glacier melt contributions to summer streamflow (Leone et al., 2025). During this event, glacier runoff increased two- to threefold compared to the 2011-2023 period, primarily due to an earlier onset and prolonged duration of the melt season, intensified melt rates, and an earlier seasonal peak in glacier contribution (Leone et al., 2025). Similarly, (Bozzoli et al., 2024) found that snow depth in the Alps has declined over the past century, particularly below 2000 m, mainly due to rising temperatures, despite slight increases in winter precipitation. Together, these studies highlight the central role of temperature-driven snow processes in shaping streamflow and drought dynamics in Alpine regions. The observed and projected shifts toward reduced snow accumulation and earlier snowmelt underpin the tendency of high- and mid-elevation catchments to behave more like lower-elevation, rainfall-dominated systems under climate change. The dominance of snowmelt and cold snow season droughts, along with the projected increase in severe winter droughts, expressed as higher deficit occurrence and longer duration, further underscores the critical role of warming in driving more extreme drought conditions in the Alps (Brunner et al., 2019, 2022c; Chartier-Rescan et al., 2025).

6. Conclusion

This study reveals clear seasonal shifts in drought characteristics and their dominant drivers across Italian Alpine catchments under climate change. In the Adige basin, droughts consistently cluster into two main periods, a spring peak from February to mid-April and a summer peak from May to September. While this bimodal pattern persists, the timing of summer drought peaks shifts earlier under both RCP4.5 and RCP8.5, reflecting changes in snowmelt dynamics and rainfall availability projected for future periods.

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Projected drought characteristics indicate substantial changes. Drought duration remains largely stable, generally shorter than 70 days in the far future, although winter droughts can exceed 100 days. At the same time, drought severity is projected to increase markedly in winter and spring, whereas summer droughts severity decreases slightly, resulting in shorter but more intense drought events. Number of drought events is expected to rise sharply, by more than 100% across all seasons, particularly in summer, spring, and winter. Seasonal variations in minimum flows show decreases in lower-elevation catchments, linked to rainfall-driven droughts or snow deficits, while higher-elevation catchments exhibit increases in winter and spring, reflecting the influence of snow contribution decrease and early snowmelt.

The seasonal shifts and intensification of droughts are strongly elevation dependent. High-elevation catchments (>1500 m) increasingly exhibit low-elevation-like flow regimes due to reduced snow accumulation and earlier snowmelt, whereas lower-elevation catchments (<1500 m) become more strongly influenced by rainfall deficits. The analysis of drought drivers further emphasizes this transition. In the past, snowmelt, glacier melt, and cold snow season processes dominated high-elevation catchments, but future projections indicate that rainfall-deficit droughts will become the primary driver across the basin, even as snowmelt and cold snow season droughts remain important at high elevations. These changes are tightly linked to temperature-driven processes, including earlier snowmelt and diminished snow reserves, which are projected to increase drought severity, particularly during winter and spring.

Overall, the findings demonstrate that climate change will fundamentally reshape drought seasonality, intensity, and drivers in Italian Alpine catchments. Earlier snowmelt, reduced snow contribution, and enhanced evapotranspiration are expected to increase drought severity, shift summer peaks earlier, and promote rainfall-dominated hydrology. These transformations carry major implications for water management, hydropower, irrigation, and tourism, highlighting the need for adaptation strategies that account for both seasonal and elevational differences in drought response.

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Author contributions

S. Bouabdelli: conceptualization, methodology, data curation, formal analysis, visualization, writing original draft. M. Morlot: data curation, review and editing. C. Massari: conceptualization, review and editing. G. Formetta: conceptualization, methodology, supervision, review and editing, funding acquisition.

Competing interests

The authors declare there are no conflicts of interest for this manuscript.

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Appendix

Tables

Gauge station	Longitude	Latitude	Total area (km^2)	Mean elevation	Corine land cover CLC18 (Top2 classes)	Glaciers
Adige A Spondigna	10.603	46.637	669.44	2133.57	1-Barren and Sparsely Vegetated 41% 2-Forests 27%	TRUE
Passirio A Merano	11.176	46.681	411.22	1860.82	1-Barren and Sparsely Vegetated 40% 2-Forests 31%	TRUE
Rienza A Stegona	11.922	46.791	1275.93	1886.01	1-Forests 48% 2-Barren and Sparsely Vegetated 29%	TRUE
Malé	10.916	46.348	465.56	2033.36	1-Forests 44% 2-Barren and Sparsely Vegetated 29%	TRUE
San Bernardo Rabbi	10.845	46.400	102.68	2227.44	1-Barren and Sparsely Vegetated 62% 2-Forests 30%	TRUE
Trento Fersina	11.118	46.044	164.56	1084.49	1-Forests 69% 2-Agriculture 13%	FALSE
Adige A Ponte Adige	11.304	46.483	2705.54	1898.69	1-Barren and Sparsely Vegetated 37% 2-Forests 31%	TRUE
Isarco A Bolzano Sud	11.303	46.459	4191.93	1730.73	1-Forests 50% 2-Barren and Sparsely Vegetated 23%	TRUE
Isarco A Campo Di Trens	11.478	46.871	511.28	1902.77	1-Forests 36%	TRUE

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					2-Barren and Sparsely Vegetated 30%	
Soraga	11.667	46.394	207.12	2123.25	1-Forests 45% 2-Barren and Sparsely Vegetated 36%	TRUE
Villa Lagarina	11.038	45.913	10160.74	1668.15	1-Forests 48% 2-Barren and Sparsely Vegetated 24%	TRUE

605 **Table A1: Attributes and geographic coordinates of the 11 gauging stations and their delineated upstream basins in the Adige River basin. Columns include basin ID, station name, Corine land cover type, total basin area (km²), mean elevation (m), and coordinates in WGS84 (EPSG:4326). The total area, land cover and mean elevation represent the characteristics of the sub-basin upstream of each gauging station.**

N.	GCM (Global Climate Model)	RCM (Regional Climate Model)	Institution
1	CNRM-CERFACS-CM5	KNMI-RACMO22E	CNRM, KNMI
2	ICHEC-EC-Earth	CLMcom-CCLM4-8-17	ICHEC, CLMcom
3	ICHEC-EC-Earth	DMI-HIRHAM5	ICHEC, DMI
4	ICHEC-EC-Earth	GERICS-REMO2015	ICHEC, GERICS
5	ICHEC-EC-Earth	KNMI-RACMO22E	ICHEC, KNMI
6	ICHEC-EC-Earth	SMHI-RCA4	ICHEC, SMHI
7	MOHC-HadGEM2-ES	DMI-HIRHAM5	MOHC, DMI
8	MOHC-HadGEM2-ES	KNMI-RACMO22E	MOHC, KNMI
9	MOHC-HadGEM2-ES	SMHI-RCA4	MOHC, SMHI
10	MPI-M-MPI-ESM-LR	MPI-CSC-REMO2009	MPI
11	MPI-M-MPI-ESM-LR	SMHI-RCA4	MPI, SMHI
12	NCC-NorESM1-M	GERICS-REMO2015	NCC, GERICS
13	NCC-NorESM1-M	SMHI-RCA4	NCC, SMHI

Table A2: Climate model combinations (GCM-RCM) used as input for hydrological simulations with A-HDT hydrological model.

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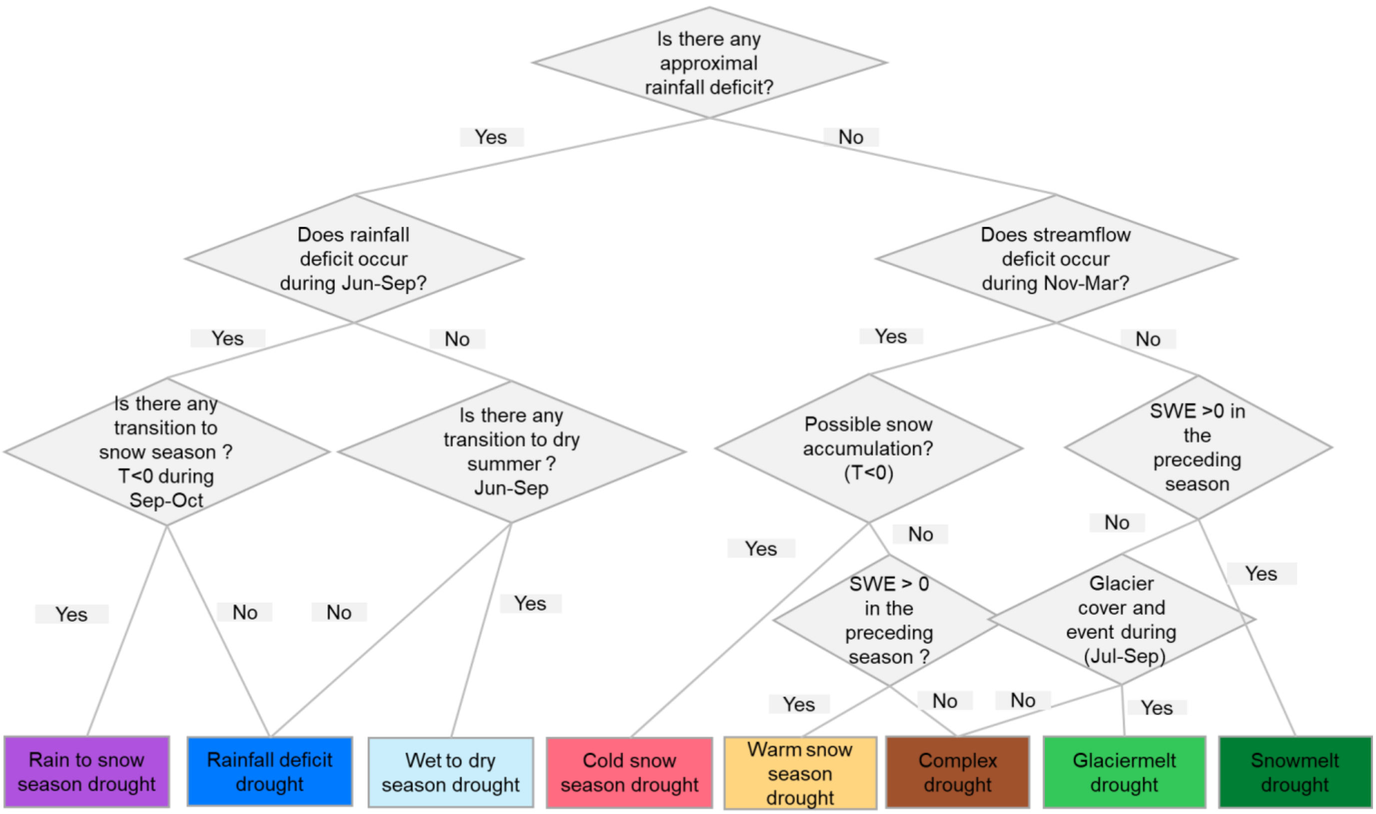
Figures



610 **Figure A1: Illustration of drought classification scheme compiled based on the drought type descriptions provided in Brunner et al., (2022).**

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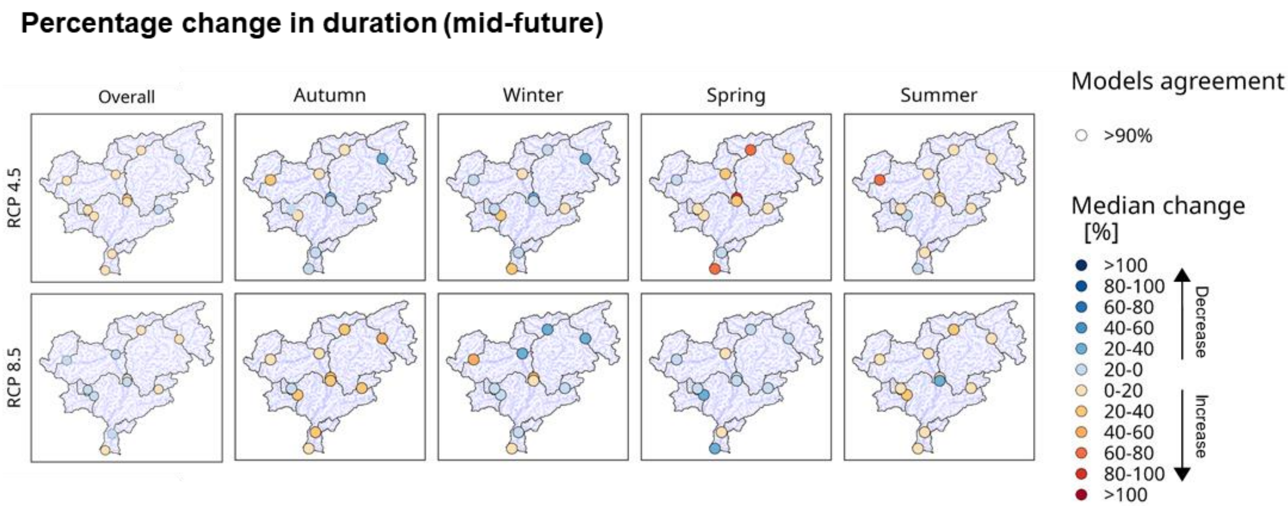

Figure A2: Projected changes in drought duration under climate change for the RCP4.5 and RCP8.5 scenarios for the mid future (2045-2074). Median values of percentage change are shown in colour and agreement on the sign of change among models is indicated by black circles.

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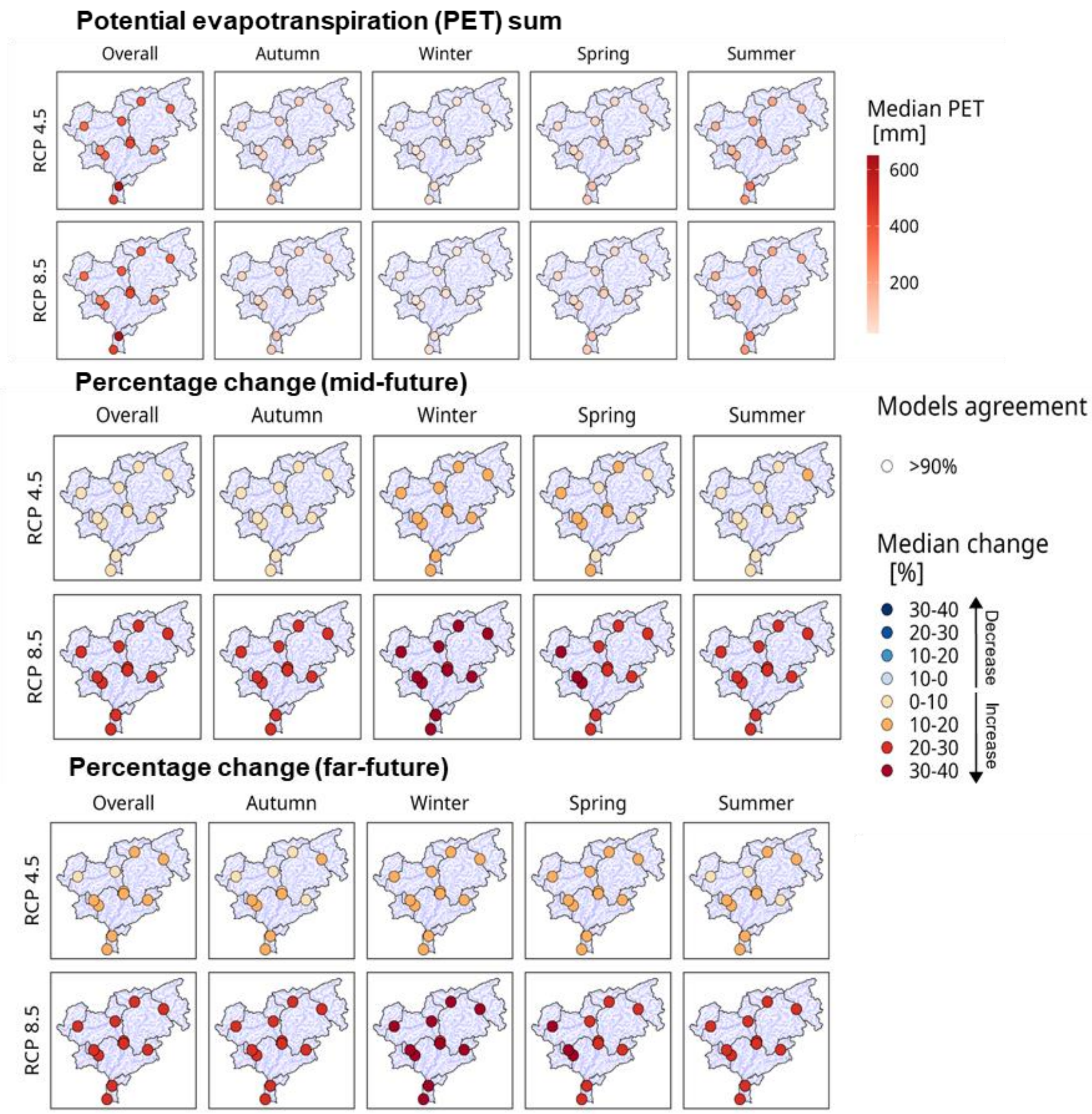

625 **Figure A3: Potential evapotranspiration (PET) sum during the reference period (1989-2018), and the projected changes under climate change for the RCP4.5 and RCP8.5 scenarios for the mid (2045-2074) far (2070-2099) future. Median values are shown in colour. For the percentage changes, agreement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

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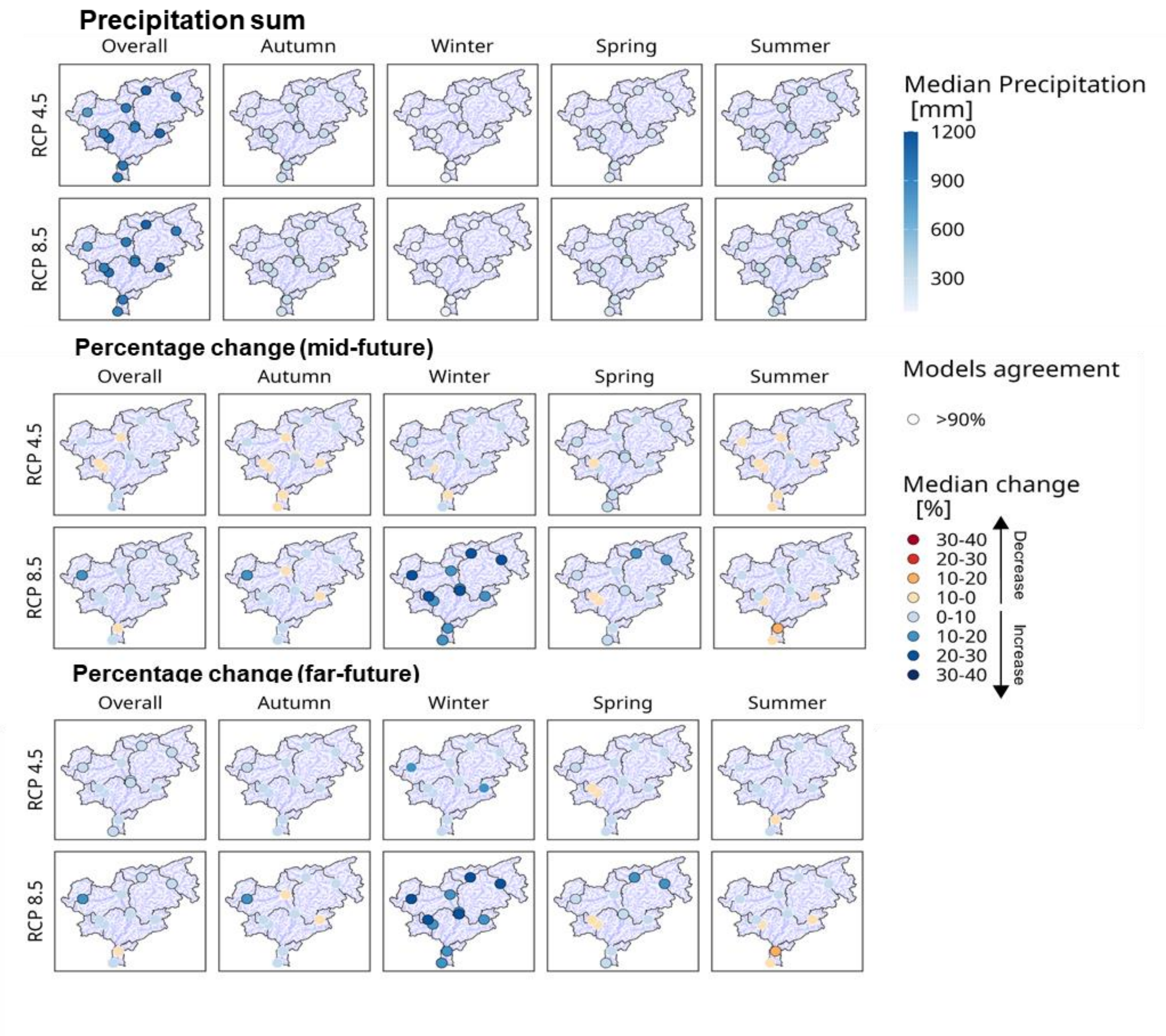

Figure A4: Precipitation sum during the reference period (1989-2018), and projected changes under climate change for the RCP4.5 and RCP8.5 scenarios for the mid (2045-2074) far (2070-2099) future. Median values are shown in colour. For the percentage changes, agreement on the sign of change among models is indicated by black circles.

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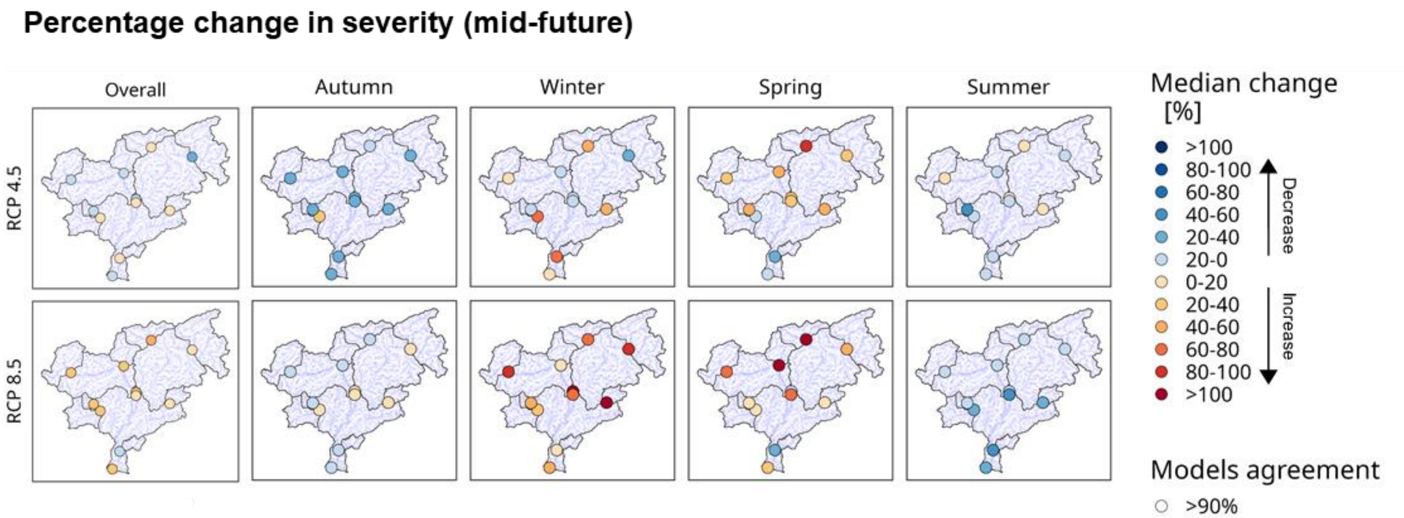

Figure A5: Projected changes in drought severity under climate change for the RCP4.5 and RCP8.5 scenarios for the mid future (2045-2074). Median values of percentage change are shown in colour and agreement on the sign of change among models is indicated by black circles.

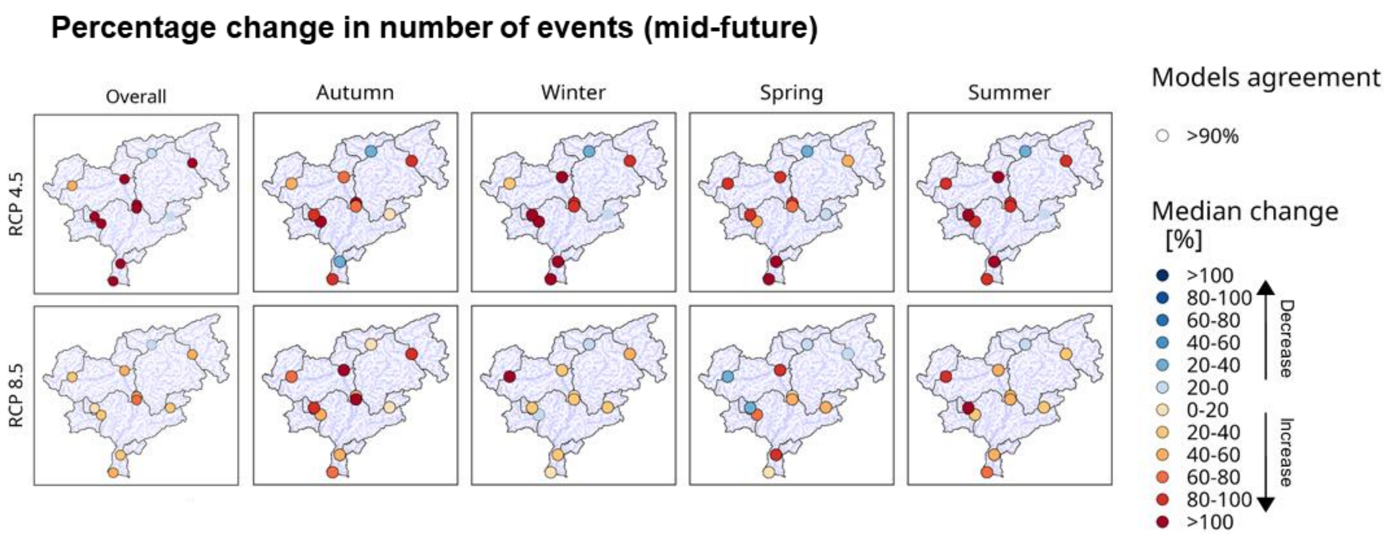

Figure A6: Projected changes in number of drought events under climate change for the RCP4.5 and RCP8.5 scenarios for the mid future (2045-2074). Median values of percentage change are shown in colour and agreement on the sign of change among models is indicated by black circles.

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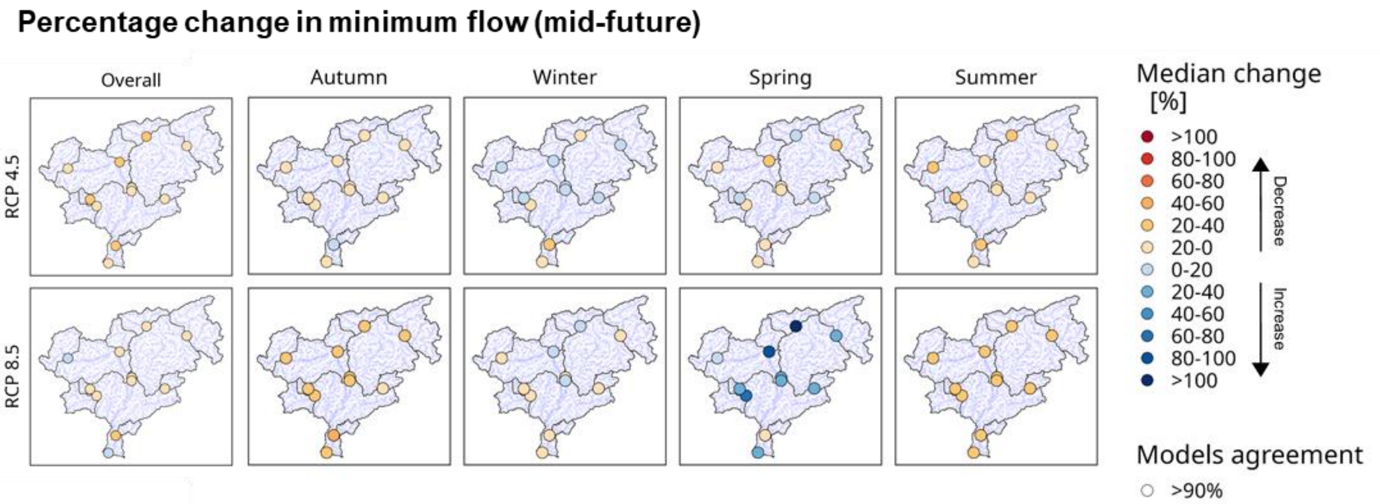

Figure A7: Projected changes in drought minimum under climate change for the RCP4.5 and RCP8.5 scenarios for the mid future (2045-2074). Median values of percentage change are shown in colour and agreement on the sign of change among models is indicated by black circles.

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