Future runoff regime changes and their time of emergence for 93 catchments in Switzerland

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Abstract. Assessments of climate change impacts on runoff regimes are essential for adaptation and mitigation planning. Changing runoff regimes and thus changing seasonal patterns of water availability have strong influence on various sectors such as agriculture, energy production or fishery. In this study, we use the most up to date local climate projections for Switzerland (CH2018) that were downscaled with a post-processing method (quantile mapping). This enables detailed information on changes in runoff regimes and their time of emergence for 93 rivers in Switzerland under three emission pathways RCP2.6, RCP4.5, and RCP8.5.

Changes in seasonal patterns are projected with increasing winter runoff and decreasing summer and autumn runoff. Spring runoff is projected to increase in high elevation catchments and to decrease in lower lying catchments. Despite strong increases in winter and partly in spring, the yearly mean runoff is projected to decrease in most catchments. Results show a strong elevation dependence for the signal and magnitude of change. Compared to lower lying catchments, runoff changes in high elevation catchments (above 1500 masl) are larger in winter, spring, and summer due to the strong influence of reduced snow accumulation and earlier snow melt as well as glacier melt. Under RCP8.5 (RCP2.6) and for catchments with mean altitude below 1500 masl, average relative runoff change in winter is +27% (+5%), in spring -5% (-6%), in summer -31% (-4%), in autumn -21% (-6%), and -8% (-4%) throughout the year. For catchments with mean elevation above 1500 masl, runoff changes on average by +77% (+24%) in winter, by +28% (+16%) in spring, by -41% (-9%) in summer, by -15% (-4%) in autumn, and by -9% (-0.6%) in the yearly mean. The changes and the climate model agreement on the signal of change increase with increasing global mean temperatures or stronger emission scenarios. This amplification highlights the importance of climate change mitigation. Under RCP8.5, early times of emergence in winter (before 2065; period 2036-2065) and summer (before 2065) were found for catchments with mean altitudes above 1500 masl. Significant changes in catchments below 1500 masl emerge later in the century. However, not all catchments show a time of emergence in all seasons and in some catchments the detected significant changes are not persistent over time.

1 Introduction

Anthropogenic climate change is unequivocal and will affect regional and local hydrology (IPCC, 2013; IPCC, 2014a; IPCC, 2014b). Thanks to major research efforts, projections of regional and local temperature and precipitation changes became more precise and more reliable. The new Swiss Climate Change Scenarios (CH2018) are the result of a large modelling effort to downscale regional climate projections to local scales for Switzerland (CH2018, 2018). The projected warming in Switzerland will likely be stronger than the global mean warming: Without major mitigation efforts, mean temperatures are projected to increase by up to 6.8°C by end of the 21st century in Switzerland under a RCP8.5 scenario. This strong increase in temperatures is companied by changes in many other hydrologically relevant variables such as precipitation amounts, precipitation type (snow vs. rain), and glacier volumes. The projected combination of increasing temperatures, changing precipitation patterns, retreating glaciers, and changes in snowpack potentially has a strong impact on runoff regimes. Runoff regimes reflect the integral response in time and space of the hydrological conditions within a catchment and hence water supply. Understanding and assessing changes in runoff regimes is crucial for many different sectors such as agriculture, fishery, hydropower generation, and tourism. Assessments of climate change impacts on river runoff are therefore particularly important for decision makers in terms of adaptation planning but can also serve as a basis for mitigation policies.

Several studies on climate change impacts on the hydrology in Switzerland have been conducted in recent years focussing on changes in runoff regimes (Horton et al., 2006; Koeplin et al., 2012; Koeplin et al., 2014; Addor et al., 2014, Milano et al., 2015), on changes in low flows (Jenicek al., 2018; Brunner et al., 2019a,b), on changes in high flows (Keller et al., 2018; Brunner et al., 2019a), or on glaciated catchments (Huss et al., 2008; Farinotti et al., 2012; Finger et al., 2013; Huss et al., 2014, Fatichi et al., 2015; Etter et al., 2017). Studies on climate change impacts on different aspects of the hydrology in the Alpine area have also been carried out in Austria (e.g. Hanzer et al., 2018; Wijngaard et al., 2016; Prasch et al., 2011; Weber et al., 2010; Tecklenburg et al., 2012), in Italy (e.g. Groppelli et al., 2011), in Germany (e.g. Hattermann et al., 2015; Nilson et al., 2014), and in France (e.g. Ruiz-Villanueva et al., 2015, Vidal et al., 2016). Most of these studies are case studies or focus on selected aspects of the hydrology. Previous studies focusing on changes in runoff regimes and including many catchments with different properties in Switzerland (Horton et al., 2006; Koeplin et al., 2012; Koeplin et al., 2014; Addor et al., 2014) found a shift in seasonality with increasing winter runoff, decreasing summer runoff, unchanging yearly mean runoff for lower lying catchments and strongly increasing yearly mean runoff for high alpine catchments. However, these studies are either based on older climate model generations or on climate simulations downscaled with a delta change approach. This approach does not capture changes in variability and the transient properties of climate change. More sophisticated downscaling approaches such as quantile mapping (Teutschbein and Seibert, 2012; Gudmundsson et al., 2012) have been developed. They not only correct for the mean bias but for the full distribution and are applicable to long-term climate simulations and allow establishing transient scenarios. Using quantile mapping as downscaling approach can result in partly different runoff characteristics. This has been shown for one test catchment by Roessler et al. (2018). Therefore, the present study is based on the Hydro-CH2018-Runoff ensemble (Muelchi et al., 2020; Muelchi et al., submitted) run with the most up to date local climate change scenarios for Switzerland (CH2018), which used the quantile mapping approach to downscale the coarse climate model output. The Hydro-CH2018-Runoff ensemble includes transient daily simulations (1981-2099) for 93 catchments in Switzerland and three different greenhouse gas (GHG) concentration pathways: RCP2.6, RCP4.5, and RCP8.5. The new ensemble allows for a detailed quantification of changes in runoff regimes. In this study, we investigate changes in runoff regimes and their seasonality under different RCP scenarios. The transient property of the simulations enables the estimation of the time of emergence of those changes. The time of emergence reflects the time when the climate signal emerges significantly from natural variability and is of particular importance to the question of how much time is left for adaptation planning. In this study, we not only analyse the time of emergence but also its evolution over time. Also, the ensemble allows for the quantification of changes by different global warming levels as these warming levels are policy relevant. The framing of the results as a function of global mean temperature change rather than time allows for a direct link to the Paris agreement target providing information on expected changes associated with a +2°C world and the consequences of missing this target. In this study, we assess changes for global warming levels of +1.5°C, +2°C, and +3°C.

2 Data

For this study, we use the Hydro-CH2018-Runoff ensemble of daily discharge simulations for 93 medium-sized catchments in Switzerland (Muelchi et al., 2020; Muelchi et al., submitted). The catchments cover a wide variety of catchment characteristics with different governing hydrological processes distributed all over Switzerland (Fig. 1). The hydrological modelling system PREVAH (Viviroli et al., 2009) is used for simulating the hydrological response to the climate change scenarios. PREVAH is a semi-distributed model based on hydrological response units and includes different submodels to account for important hydrological processes related to snow, glacier, and soil moisture dynamics, as well as evapotranspiration. PREVAH was calibrated and validated for each catchment (for more details see Muelchi et al., submitted). The calibrated parameters were kept constant for the simulation of runoff under climate change and the land use was held unchanged for non-glaciated catchments. The minor impact of land use changes on changes in the runoff regime for Switzerland was assessed by Koeplin et al. (2014). For glaciated catchments, glacier extents were updated every 5 years according to the glacier projections by Zekollari et al. (2019) that are based on the same climatic data set. The land use of areas where glaciers disappear was replaced by rock for areas above 3000 masl and by bare soil for areas below 3000 masl.
The meteorological input used for the simulations consists of the new Swiss climate change scenarios CH2018 (CH2018, 2018). The CH2018 scenarios used EURO-CORDEX simulations (Jacob et al., 2014; Kotlarski et al., 2014) and applied a statistical downscaling (quantile mapping; Teutschbein and Seibert, 2012; Gudmundsson et al., 2012) on the available chains of Global Circulation Models and Regional Climate Models (GCM-RCM chains). The results consist of gridded high-resolution (2x2 km) daily temperature and precipitation data for Switzerland for the period 1981-2099. This dataset was then used to drive the hydrological model resulting in the Hydro-CH2018-Runoff ensemble consisting of daily runoff time series

for 1981-2099 for each of the GCM-RCM chain. The Hydro-CH2018-Runoff ensemble consists of simulations for three different GHG concentration pathways: 8 simulations under RCP2.6, 16 simulations under RCP4.5, and 20 simulations under RCP8.5. The GCM-RCM chains and their underlying emission scenarios used for this study are listed in table 1. For the analysis of changes in runoff constrained by different warming levels, the global mean temperatures of the driving GCMs (CMIP5, Taylor et al., 2012) were used.

3 Methods

3.1 Study area

The study area consists of 93 catchments distributed over Switzerland (Fig. 1) and covering a wide range of catchment characteristics with an average catchment size of 314 km^2 (range 14-1700 km^2) and a mean altitude of 1344 masl (range 476-2700 masl). 22 out of 93 catchments are glaciated with a varying degree of glaciation between 0.2-22%. The present runoff regimes range from glacier fed catchments in high alpine areas, mainly snow driven catchments (mean altitude above 1550 masl) in the Alps and Prealps to rain fed catchments predominant in the Swiss Plateau and at lower elevations in the southern part of Switzerland. Six catchments (highlighted in Fig. 1) are used as example catchments representing typical runoff regimes: Rosegbach – highly glaciated (22%), Kander – partially glaciated (5%), Plessur – high-alpine snow influenced, Emme – pre-alpine rain and snow influenced, Venoge – lowland rain dominated, and Verzasca – southern-alpine rain and snow dominated. An overview of the catchment characteristics can be found in the Supplement (table S1).

3.2 Changes in runoff regimes

The simulations are analyzed using yearly and seasonal ~~mean~~ changes under the three RCPs (2.6, 4.5, 8.5). All changes are specified for 30-year periods to remove the inter-annual variability. The reference period covers the years 1981-2010 and is compared with the far future period 2085 (2070-2099). The median among all simulations within an RCP pathway is considered as the best estimate. To get an indication of the robustness of the estimation, the changes are highlighted when at least 90% of the simulations show the same direction of change (positive or negative). For the analysis of changes in runoff regime, monthly means for 30-year periods were calculated with the median representing the best estimate and the uncertainty band showing the full range among all models within an RCP. To simplify the interpretation of the results, this study only focuses on changes by 2085 under RCP8.5 and RCP2.6. These two emission scenarios reproduce the potential range of changes in the full Hydro-CH2018-Runoff ensemble. Results for the near future period of 2060 (2045-2074) and for RCP4.5 can be found in the Supplement.

3.3 Changes with increasing global mean temperatures

For the analysis of changes as a function of global mean temperature change, temperature targets of +1.5°C, +2°C, and +3°C with respect to pre-industrial state were defined. Since the temperature targets are defined with respect to the pre-industrial state, the observed warming between the pre-industrial state (1864-1900) and the reference period (1981-2010) has to be subtracted from the temperature targets. The observed warming is estimated to be 0.6°C and thus the remaining global warming for the 1.5°C, 2°C, and 3°C temperature target is 0.9°C, 1.4°C, and 2.4°C, respectively (Morice et al., 2012; for technical details: CH2018, 2018). For each of the driving GCMs used in the Hydro-CH2018-Runoff ensemble for RCP8.5, we computed differences in moving 30-year averages of global mean temperatures compared to the reference period. The time periods (30-year windows) when global mean temperature change exceed +0.9°C, +1.4°C, and +2.4°C were selected for each GCM. Subsequently, the seasonal and yearly changes in runoff were extracted for each of the time periods and the driving GCM in the GCM-RCM combination. Again, catchments with robust signals are highlighted, ~~where~~ at least 90% of simulations agree on the ~~signal~~ direction.

3.4 Time of emergence of seasonal changes

The time of emergence indicates the time of significant changes in the distribution of the seasonal and yearly means. The Kolmogorov-Smirnov test was used to test whether two 30-year samples of seasonal or yearly means are drawn from the same distribution. This test was conducted on the distributions of moving 30-year windows and the distribution of the reference period. This was done for each simulation under RCP8.5 and each catchment separately. Constraining the analysis to the RCP8.5 ensemble was motivated by the sufficiently large number of simulations (20 simulations) within the ensemble. The time of emergence is then defined as the last year of 30-year moving window where the Kolmogorov-Smirnov test was rejected for the first time at 95% significance. Significance of changes in the seasonal and yearly mean are discussed when at least 66% of the models detect a significant change in the same 30-year window. Since the time of emergence may not be constant in time, we also analyze the temporal evolution of rejections of the null hypothesis (p-values smaller than 0.05).

4 Results

4.1 Seasonal and yearly mean changes

Changes in the multimodel median of seasonal and yearly mean runoff by end of the century (2085) are shown in Fig. 2 for RCP8.5 and in Fig. 3 for RCP2.6 (see Fig. S1 for RCP4.5 and Figs. S2-S4 for the period 2060). Highlighted catchments show changes where at least 90% of the models agree on the signal of change.

In winter, all catchments show positive mean runoff changes ~~compared to the reference period~~ under RCP8.5 by end of the century (Fig. 2a). The mean runoff changes range from +2% to +221%, where strongest changes are found in higher elevation catchments. The mean change among all catchments is +48%. 84 out of 93 catchments show strong agreement (>=90%) on the signal direction. Under RCP2.6, 87 out of 93 catchments show positive changes with mean runoff changes across all catchments of +13% (Fig. 3a). However, only 41 catchments show robust model agreement on the signal direction. The range among the catchments is between -3% and +58%, again with stronger changes in the mountainous areas.

In spring, both positive and negative changes in mean runoff are found (Figs. 2b and 3b). The mean change across all catchments is +9% under RCP8.5 (Fig. 2b). While most of the lower catchments show a decrease in runoff (up to -21%), the higher elevation catchments exhibit an increase (up to +166%) under RCP8.5. The strong increase in spring runoff is mainly found in the highest elevation catchments (Fig. 2b), where snowmelt is enhanced due to higher temperatures by shifting the snowmelt season from early summer to spring (not shown). However, only 34 out of 93 catchments exhibit robust changes across the climate models. Compared to the high emission scenario, the changes in the low emission scenario (RCP2.6) tend to be more moderate and some catchments change the signal of change from positive changes in RCP8.5 to negative changes in RCP2.6 (Fig. 3b). Thus under RCP2.6, the changes range from -15% to +70% with a slightly positive mean (+3%) across all catchments. 58 catchments show robust changes in spring mean runoff under RCP2.6.

In summer and under RCP8.5, all catchments show a decrease in mean runoff ranging from -16% to -59% with mean change of -35% across all catchments (Fig. 2c). Again, stronger changes are found in higher elevation catchments, where summer runoff is projected to decrease by up to half of the runoff of the reference period. Except for one catchment, the agreement on the signal direction among the climate models is robust. Under RCP2.6, the signals and changes are less clear (Fig. 3c). The average change is across all catchments is negative (-6%) but mean runoff change ranges from -26% to +4%. 9 out of 93 catchments show positive but non robust mean runoff changes in summer while 34 catchments yield robust negative signals.

In autumn, all but one catchment show decreasing runoff under RCP8.5 (Fig. 2d). Changes range from -36% to +4% with an average change of -19% across all catchments. More than 50% of the catchments (50 catchments) reveal robust changes. In contrast to the changes in summer, the autumn runoff tends to decrease stronger in the lower lying catchments than in the higher elevation catchments. Under RCP2.6, the changes are much smaller compared to RCP8.5 with an average change of -5% (ranging from -20% to +10%) (Fig. 3d). The changes are also less robust with only 17 catchments showing good agreement on the signal of change.

Despite the strong increases in winter and partly in spring, the yearly runoff is projected to decrease by -8% (range: -23% to +4%) under RCP8.5 (Fig. 2e) and -2% (range: -13% to +11%) under RCP2.6 (Fig, 3e) on average. While 82 (out of 93) catchments show negative changes under RCP8.5, only 65 catchments yield negative changes under RCP2.6. However, the robustness on the year mean runoff change signal is weaker than for the seasonal mean changes.

Considering the results above, the changes in seasonal and yearly mean runoff are strongly dependent on the mean elevation of the catchment. This dependence is highlighted in Fig. 4 where changes in runoff are plotted against mean altitude of the catchments. The higher elevation catchments generally show stronger changes in winter, spring, and summer compared to the lower elevation catchments. For autumn and yearly runoff, no distinct pattern can be seen. Under RCP8.5 and for catchments with mean altitude below 1500 masl, average ~~relative~~ change is +27% in winter, -5% in spring, -31% in summer, -21% in autumn, and -8% in the yearly mean (Fig. 4a). For catchments with mean elevation above 1500 masl, runoff changes on average by +77% in winter, by +28% in spring, by -41% in summer, by -15% in autumn, and by -9% in the yearly mean. However, the changes in the higher elevation catchments are less pronounced under RCP2.6 with an average change in catchments below 1500 masl of +5% in winter, -6% in spring, -4% in summer, -6% in autumn, and -4% in yearly mean runoff (Fig. 4b). In higher elevated catchments (>1500 masl), the mean changes under RCP2.6 amount to +24% in winter, +16% in spring, -9% in summer, -4% in autumns, and -0.6% in the year.

4.2 Changes in the runoff regime

Changes in runoff regime for six example catchments representing typical runoff regime types in Switzerland: Rosegbach – Pontresina, Kander – Hondrich, Plessur – Chur, Emme – Emmenmatt, Venoge – Ecublens, and Verzasca – Lavertezzo (highlighted catchments in Fig. 1) are depicted in Fig. 5. Again, results for RCP4.5 can be found in the Supplement (Fig. S5). The runoff regimes with absolute monthly mean runoff presented in this chapter help to interpret the relative changes of seasonal and yearly runoff means discussed in section 4.1.

The glaciated catchment Rosegbach-Pontresina exhibits strong changes in all months under RCP8.5 (Fig. 5a). The typical glacier runoff regime with low flows in winter and peak flows in summer in the reference period changes to a more nival type regime with a peak runoff in late spring and early summer under RCP8.5 (Fig. 5a). While there are strong relative (percent) increases in the winter months, the contribution of winter runoff to the total runoff remains small. The mean runoff between June and September drops dramatically due to missing snow and glacier melt contributions. However, runoff in late spring and summer remains the major contributor to the yearly volume. Under RCP2.6, the changes for winter, spring, and autumn runoff are small. In summer and early autumn, the runoff decreases significantly, and the summer peak shifts from July/August to June/July. The change in summer runoff under RCP2.6 is approximately halved compared to the changes under RCP8.5.

A similar behavior with a shift of the peak in the runoff regime from summer to late spring/early summer is also found for the runoff regime in the partially glaciated catchment Kander – Hondrich under RCP8.5 (Fig. 5b). The regime is characterized by a strong peak in early summer runoff in the reference period. Under RCP8.5, the summer runoff decreases significantly while winter runoff increases. This leads to a flattening of the runoff regime curve resulting in similar importance of winter and summer runoff with respect to the yearly volume. Under RCP2.6, there is also a decrease in July, August, and September, but less pronounced compared to the decrease under RCP8.5.

The nival regime of the river Plessur-Chur also experiences a shift in peak flow from June to May under both emission scenarios (Figure 5c). Due to the increase in winter and decrease in summer runoff, the regime curve flattens under RCP8.5. The results also show increasing winter runoff and decreasing summer runoff under RCP2.6 but far less pronounced than under RCP8.5.

In the reference period, the runoff regime in the pluvial catchment Emme – Emmenmatt shows a peak in spring and early summer due to snowmelt and stable mean runoff from August to February (Figure 5d). By end of the century under RCP8.5, the peak runoff in spring almost disappears. The runoff decreases strongly in the summer months and less strongly in the autumn months.

The shape of the runoff regime curve of the river Venoge – Ecublens remains the same for the references period and the two emission scenarios with higher runoff in winter and lower runoff in summer (Figure 5e). While the regime changes only marginally under RCP2.6, the amplitudes under RCP8.5 becomes more distinct with higher winter runoff and lower summer runoff than in the reference period. However in comparison to other catchments this change is smaller.

The southern alpine catchment Verzasca – Lavertezzo shows a two peaked runoff regime with a first runoff peak in late spring and a second runoff peak autumn in the reference period (Figure 5f). This pattern is still present by end of the century under both scenarios. However, the amplitude of the peaks is less pronounced under RCP8.5 because of increasing winter runoff and decreasing spring and summer runoff.

Summarizing the differences under RCP8.5 and RCP2.6 shows that the signal of change under RCP2.6 is in almost all months and catchments equal to the signal under RCP8.5. Comparisons with RCP4.5 (see Fig. S5 in the Supplement) show that the magnitude of changes increases the stronger the emission scenario and the more distant in time. Also, the model agreement on the direction of change among the climate models is weaker under the low emission scenario RCP2.6 than under RCP8.5.

4.3 Time of emergence

The time of emergence when at least 66% of the models (under RCP8.5) agree on significant changes in the distribution of seasonal and yearly means is depicted in Fig. 6. In winter, 45 out of 93 catchments show a time of emergence in the 21st century i.e., a significant change in mean flow (Fig. 6a). An elevation dependence can be identified with an earlier time of emergence in higher elevated catchments and a later time of emergence in lower lying catchments. Particularly the high alpine catchments show an early time of emergence with 2046 (period 2017-2046) as the earliest time of emergence. The mean altitude of catchments with a time of emergence earlier than 2065 is greater than 1500 masl (with one exception). Among the 48 catchments that do not show a time of emergence, 46 catchments have a mean altitude lower than 1200 masl.

In summer, 73 catchments exhibit a time of emergence and again generally an earlier time of emergence for higher elevation catchments (Fig. 6c). Catchments showing a time of emergence earlier than 2065 are all located in mountainous area with mean altitudes higher than 1500 masl (again with one exception). The earliest time of emergence in summer is found for the year 2043 (period 2014-2043). Catchments without time of emergence show a mean elevation lower than 1000 masl (with one exception).

In spring, only 20 catchments exhibit a time of emergence (Fig. 6b). Again, significant changes in the distribution is mainly found in the higher alpine catchments (above 1500 masl). 14 catchments (out of 93) exhibit a time of emergence in autumn (Fig. 6d). In contrast to the other seasons, there is no clear elevation pattern distinguishable in autumn.

For the yearly means, 11 catchments reveal a time of emergence in the 21st century (Fig. 6e). Time of emergence in the yearly mean is not restricted to high alpine catchments but only two catchments below 1500 masl show significant changes (after 2095).

In all seasons, some of the catchments do not show a time of emergence, meaning that there is no statistically significant change in the distribution of the seasonal means. Clear patterns of significant changes in the distribution of seasonal means is mainly found in winter and summer. Due to the definition of time of emergence as the last year of a moving window where the Kolmogorov-Smirnov test is rejected for the first time, the time of emergence is not necessarily persistent over time. Fig. 7 shows the temporal evolution of the time of emergence for the different seasons under RCP8.5. Most of the catchments show persistent significant changes after the first detection of a time of emergence. However, there are some catchments revealing a time of emergence in a certain period, but not showing a time of emergence afterwards. The problem of non-constant rejections affects 17 catchments in winter, 3 catchments in spring, 25 catchments in summer, and 6 catchments in autumn. Most of these catchments show a persistent time of emergence for the rest of the century few years after the first detection. However, this may lead to too early detections of time of emergence but not persistent in time.

4.4 Changes in seasonal means with warming levels

Changes in the multi-model median of seasonal and yearly mean runoff for different global warming levels is shown in Fig. 8 for warming targets +1.5°C, +2°C, and +3°C. Generally, the pattern of change with global warming levels are similar than the patterns for the two emission scenarios. The range of change between the catchments as well as the climate model agreement increases with stronger global warming levels.

In winter, the mean runoff change across all catchments is +17% for a global warming of +1.5°C, +23% for +2°C, and +35% for +3°C (Fig. 8 a-c). With stronger global warming not only the mean increases but also the range of change across the catchments. While at +1.5°C global warming the range across all catchments is between -1% and +53%, the range for the +3°C global warming is +5% to +127%. While there are two catchments showing slightly negative changes at +1.5°C warming, all catchments show positive changes for stronger warming levels. Also, the agreement across the climate models per catchment increases with increasing warming.

The mean change in spring runoff among all catchments is +4% for +1.5°C, +6% for 2°C, and +10% for 3°C global warming (Fig. 8 d-f). The changes in spring vary dependent on the elevation (see results in section 4.1) with positive changes mainly for the higher elevated catchments and negative changes for lower lying catchments. Even though the average across all catchments does only change little between warming levels, the range of change across the catchments and the model agreement per catchment increases with strong warming levels and thus the regional (elevation dependent) patterns get more pronounced.

In summer, the average among all catchments is -7% for 1.5°C global warming, -13% for 2°C warming, and -23% for 3°C global warming (Fig. 8g-j). Again, the ranges across catchments and the model agreement increase with stronger warming levels. Compared to summer, the decrease in autumn runoff is smaller with an average across all catchments of -9% for 1.5°C, -7% for 2°C, and -13% for 3°C global warming. Most catchments (89 out of 93) show a negative multimodel median for both, 1.5°C and 3°C warming levels. While only three catchments show a model agreement of more than 90% for a 1.5°C global warming, there are 43 catchments showing robust model agreement on the direction of change for a 3°C global warming.

For yearly mean runoff, the mean among all catchments is +0.2% for 1.5°C, -0.9% for 2°C, and -3.7% for 3°C. Despite the slightly positive signal for 1.5°C warming, 53 catchments out of 93 show negative changes. This number increases to 66 catchments for 2°C and 77 catchments for 3°C. Also, the model agreement increases from 3 catchments with robust model agreement for 1.5°C to 17 catchments for 3°C.

5 Discussion

Winter runoff generally increases in Switzerland due to enhanced winter precipitation and increasing temperatures with climate change (CH2018, 2018). The higher temperatures lead to more liquid precipitation (rain) and less solid precipitation (snow) in winter. This leads to less snow accumulation and thus to more direct runoff in winter. The relative changes in winter in glaciated catchments are very high, but in terms of contribution to the yearly volume still neglectable. In nival and pluvial catchments changes in winter runoff become more important in terms of water availability.

In spring, the glaciated and snow driven catchments show increasing runoff due to enhanced snowmelt (not shown), particularly in early spring. The combination of reduced snow accumulation in winter and earlier snowmelt shifts the peak in runoff regime to a month earlier. Lower lying catchments show decreasing runoff in spring due to reduced snow accumulation in winter and thus reduced available snow for snowmelt.

The summer runoff in Switzerland generally decreases with climate change. This decrease is governed by different processes according to the location and elevation of the catchments. In general, reduced summer precipitation and enhanced evapotranspiration lead to decreasing runoff in Switzerland (not shown). In high alpine regions, where summer snowmelt and glacier melt dominate the runoff generation in the reference period, the lack of available snowpack and the glacier retreat amplify the decrease in summer runoff. The large model spread in summer in glaciated catchments stems from the sensitivity of the runoff response to the glaciation of the catchment. In catchments, where not all climate projections result in a complete disappearance of glaciers, the model spread increases strongly and future glacier retreat is hence a major source of uncertainty.

Autumn runoff is also projected to decrease due to reduced precipitation and enhanced evapotranspiration (not shown, CH2018, 2018). Again, in catchments where glacier melt is important in early autumn today, this decrease is amplified. However, looking at the regime changes, the decrease in autumn runoff is most noticeable in early autumn, while in late autumn (end of October and November) the changes are less significant and can even change direction to positive values (not shown). This pattern is mainly found in very high alpine catchments, where late autumn precipitation can fall more often as liquid precipitation instead of solid precipitation and thus cannot be stored as snowpack. For the yearly mean, a decrease in runoff emerges in most catchments, however with less robust signals among the climate models. This leads to the conclusion that throughout the year there will be less water available in Swiss rivers. The shift in seasonality and thus a shift in the seasonal availability of water will impact many different sectors.

In most catchments and seasons, the signal of change is the same for the high emission scenario (RCP8.5) and the low emission scenario (RCP2.6). Changes in seasonality or in the runoff regime get amplified by higher emissions and thus by increasing global mean temperatures. This amplification due to enhanced emissions and with intensified global warming shows the large benefits of mitigation. By mitigating climate change and following the RCP2.6 pathway, the magnitude of change can be reduced or even avoided (depending on the season and the runoff regime). However, some of the seasonal changes cannot be avoided by mitigation actions, particularly in high alpine catchments, where glacier retreat is also present (on a smaller magnitude) in the low emission scenario. Responsible planners and policy maker need to adapt to this shift in seasonality.

Previous studies on climate change impacts on the runoff regime in Switzerland (e.g. Koeplin et al., 2012, 2014; Horton et al., 2006) were driven by other emission scenarios, other and fewer climate model chains, different postprocessing methods of the climate model output, and/or different hydrological models and calibration. Despite these differences the signal of change in those studies agrees in most seasons with the signals in this study. A strong elevation dependence of changes was also found by Koeplin et al. (2012). The largest difference concerns the yearly mean runoff. Koeplin et al. (2012) found an increase (up to +50%) in yearly runoff for high altitude catchments and no change for lower lying catchments in the yearly volume. In contrast, our study projects a decrease in the yearly mean runoff for high elevation catchments but also for most of the lower lying catchments. However, not all catchments show a robust decrease. This difference between our results and previous studies may arise from the transient property of the simulations, the different handling of glacier melt and the new projections of glacier extents. The Hydro-CH2018-Runoff ensemble uses transient glacier projections which are updated every 5 years in the hydrological model. Koeplin et al. (2012) used static glacier projections for 30 years. Strongest uncertainties in glaciated catchments was also found by Addor et al. (2014). Also, the difference in the input data (transient projections versus delta change projections with same baseline time series for the reference period) may add to the different signals.

Even though not all catchments show a time of emergence in the 21st century, early significant changes in the distribution of seasonal means emerge particularly in high elevation catchments. This is due to the importance of snow and glacier melt for alpine runoff regimes. With climate change, the influence of snow and glacier decreases or lacks completely due to higher temperatures and its subsequent glacier retreat. Lower lying catchments show generally a later time of emergence. Koeplin et al. (2014) also assessed a time of emergence for Swiss catchments but only based on significant changes for two scenario periods and 10 climate models. Since their climate models were post-processed with a delta change approach, only the natural variability of the reference period is reflected in their simulations. Despite these differences in methodology and data, they also found earlier time of emergence in winter and summer for high elevation catchments. While the applied definition of time of emergence is commonly used in other climate change studies (e.g. Mahlstein et al., 2010), this definition also has disadvantages. For example, if the rejection of the null hypothesis (two samples are drawn from the same distribution) is unstable in its temporal evolution, the time of emergence may be determined too early. This has been shown for some of the catchments in the present study. However, in most catchments a persistent detection of significant changes in the distribution of the seasonal means has been found shortly after the first detection of significant changes.

Different sources of uncertainty affect our results. Uncertainties arise from all steps of the modelling chain: the scenarios of GHG concentrations, the climate model chains and their boundary and initial conditions, the post-processing method, the hydrological model and its calibration, and the underlying glacier projections.

6 Conclusions

Changes in runoff regimes and their time of emergence were assessed with the new hydrological scenarios for 93 catchments in Switzerland. This study is based on the newest generation of climate change scenarios post-processed with more sophisticated methods. Compared to previous studies on runoff regime changes, the results show similar change signals for most seasons. Strongest differences were found for the high elevation catchments which is likely due to the transient property of the simulations and the implementation of more sophisticated glacier projections.

In general, winter runoff is projected to increase and summer runoff to decrease in Switzerland. The sign of change is robust across catchments, but the magnitude of change is more pronounced for high elevation catchments. Particularly in summer, when snow and glacier melt play an important role in runoff generation, glaciated catchments will face a strong decrease in runoff due the retreating glaciers. In rainfall dominated catchments, the changes are also often robust but on a smaller magnitude. While the higher elevated catchments show increasing spring runoff due to earlier snowmelt, the pluvial catchments in the lowlands will face decreasing spring runoff. A decrease in runoff is also found for autumn and yearly mean runoff in most catchments. These seasonal patterns amplify with global warming and with higher emission scenarios. Also, the model agreement among the climate models is more robust for the stronger the emission scenario and the farther future. Significant changes in the seasonal mean runoff was mainly found in summer and winter and only for few catchments in spring and autumn. Early time of emergence in winter (before 2060) and summer (before 2065) was found for higher elevation catchments above 1500 masl. Significant changes in catchments below 1500 masl emerge later in the century. However, not all catchments show a time of emergence in all seasons.

The amplification of changes by stronger global warming highlights the importance of climate change mitigation. By mitigating climate change and following the RCP2.6 pathway (global warming below 2 °C), the magnitude of change can be reduced substantially. The strong decrease in summer runoff in glaciated catchments can be strongly damped but not avoided because glacier retreat is also projected for the low emission scenario. The present study can help to support adaptation planning in various sectors by presenting detailed information on changes in mean runoff.

Data availability

The data used in this study is available under https://doi.org/10.5281/zenodo.3937485 (Muelchi et al., 2020).

Author contributions

RM performed the analysis of the results and drafted the manuscript. JS, OR, RW and OM helped in interpretation of the results. All authors reviewed the resulting data and assisted with paper writing.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1: List of used GCM-RCM chains, their initial resolution, and the available RCP.

GCM	**RCM**	**RCP8.5**		**RCP4.5**		**RCP2.6**	
		EUR-11	EUR-44	EUR-11	EUR-44	EUR-11	EUR-44
ICHEC-EC-EARTH	KNMI-RACMO22E		X		X		
	DMI-HIRMAM5	X		X		X	
	CLMcom-CCLM4-8-17	X		X			
	CLMcom-CCLM5-0-6		X				
	SMHI-RCA4	X		X		X	
MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	X		X			
	CLMcom-CCLM5-0-6		X				
	KNMI-RACMO22E		X		X		X
	SMHI-RCA4	X		X			X
MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	X		X			
	CLMcom-CCLM5-0-6		X				
	SMHI-RCA4	X		X			X
	MPI-CSC-REMO2009-2	X		X		X	
MIROC-MIROC5	CLMcom-CCLM5-0-6		X				
	SMHI-RCA4		X		X		X
CCCma-CanESM2	SMHI-RCA4		X		X		
CSIRO-QCCCE-CSIRO-Mk3-6-0	SMHI-RCA4		X		X		
IPSL-IPSL-CM5A-MR	SMHI-RCA4	X		X			
NCC-NorESM1-M	SMHI-RCA4		X		X		X
NOAA-GFDL-GFDL-ESM2M	SMHI-RCA4		X		X		

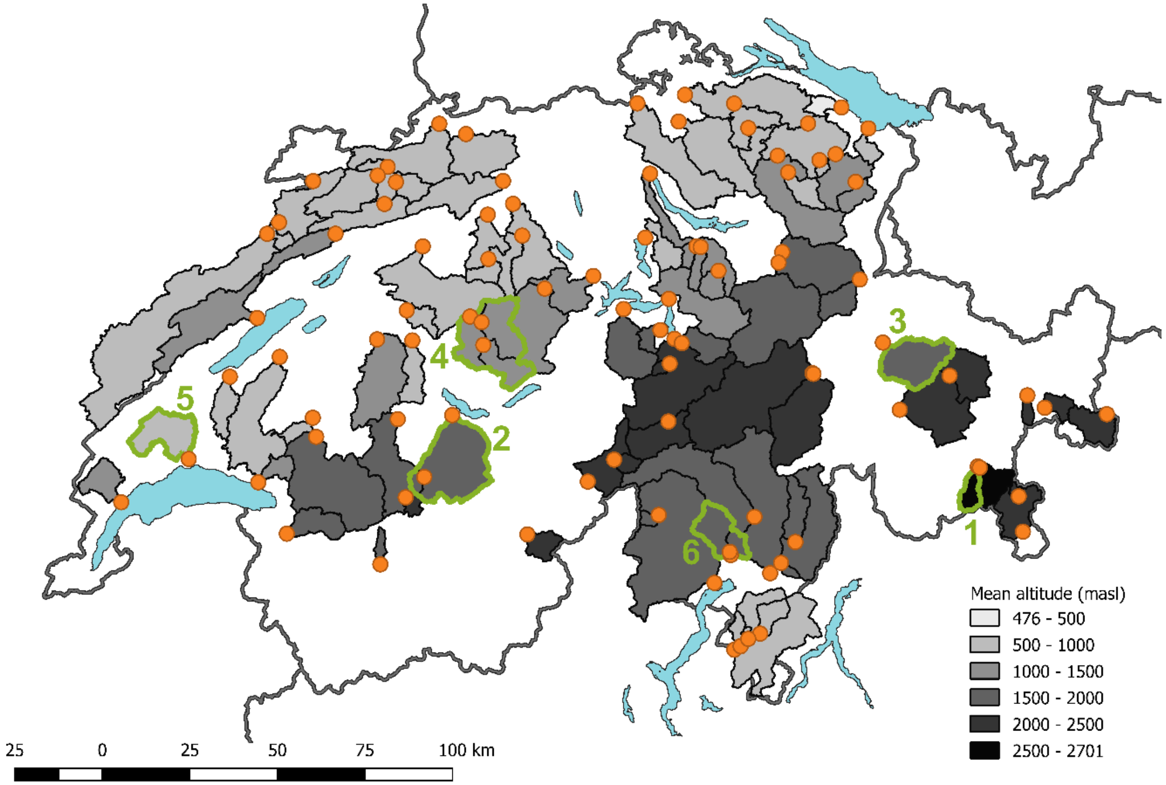

Figure 1: Overview of the study region and the location of the gauging stations (orange dots). Shadings indicate mean altitude of the respective catchment. Green contours indicate the six example catchments: Rosegbach – Pontresina (1), Kander – Hondrich (2), Plessur – Chur (3), Emme – Emmenmatt (4), Venoge – Ecublens (5), Verzasca – Lavertezzo (6).

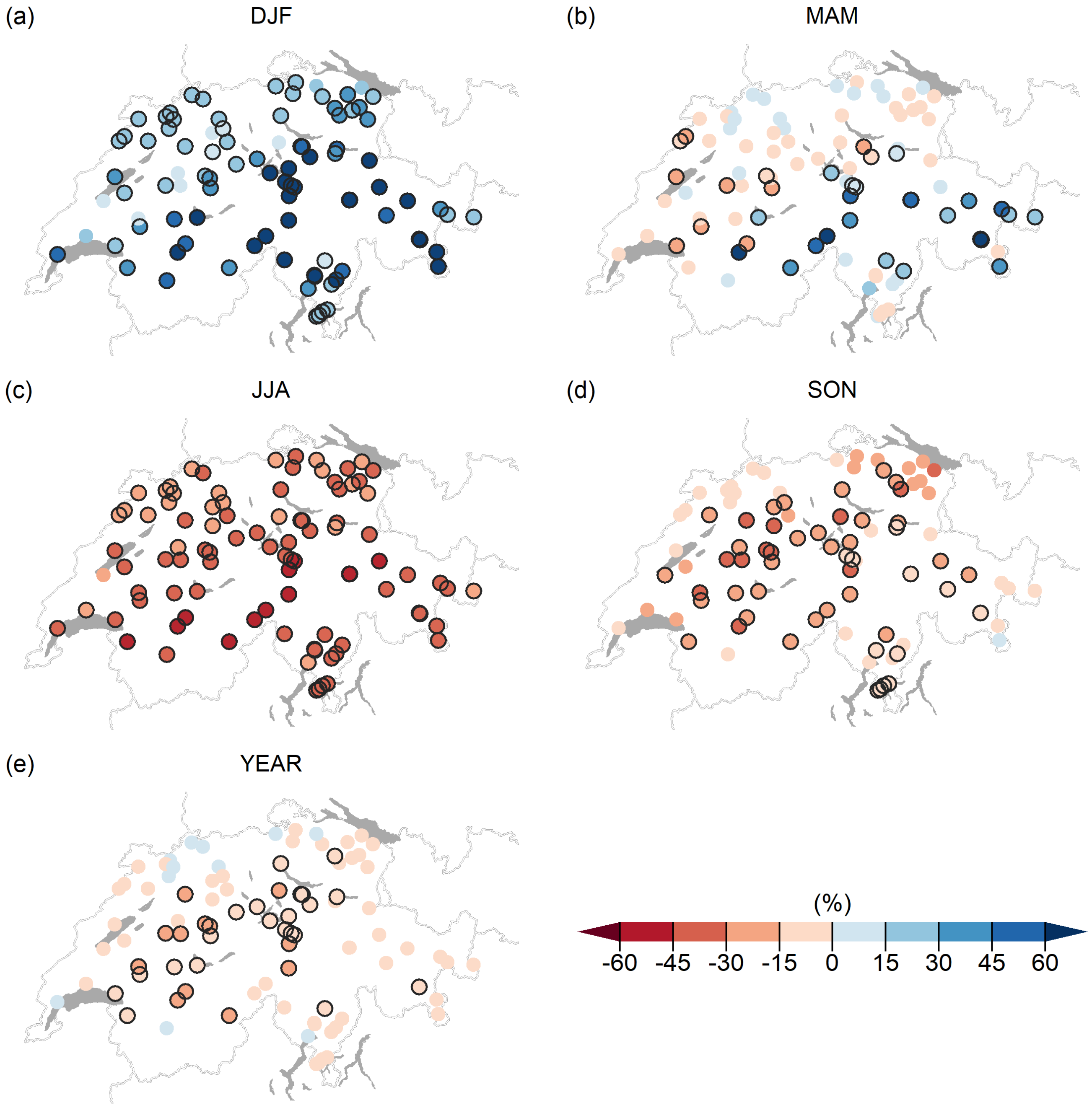

Figure 2: Multimodel median of seasonal and yearly mean changes under RCP8.5 by 2085 for winter (a), spring (b), summer (c), autumn (d), and yearly means (e). Black circles indicate changes with at least 90% of the models agreeing on the direction of change.

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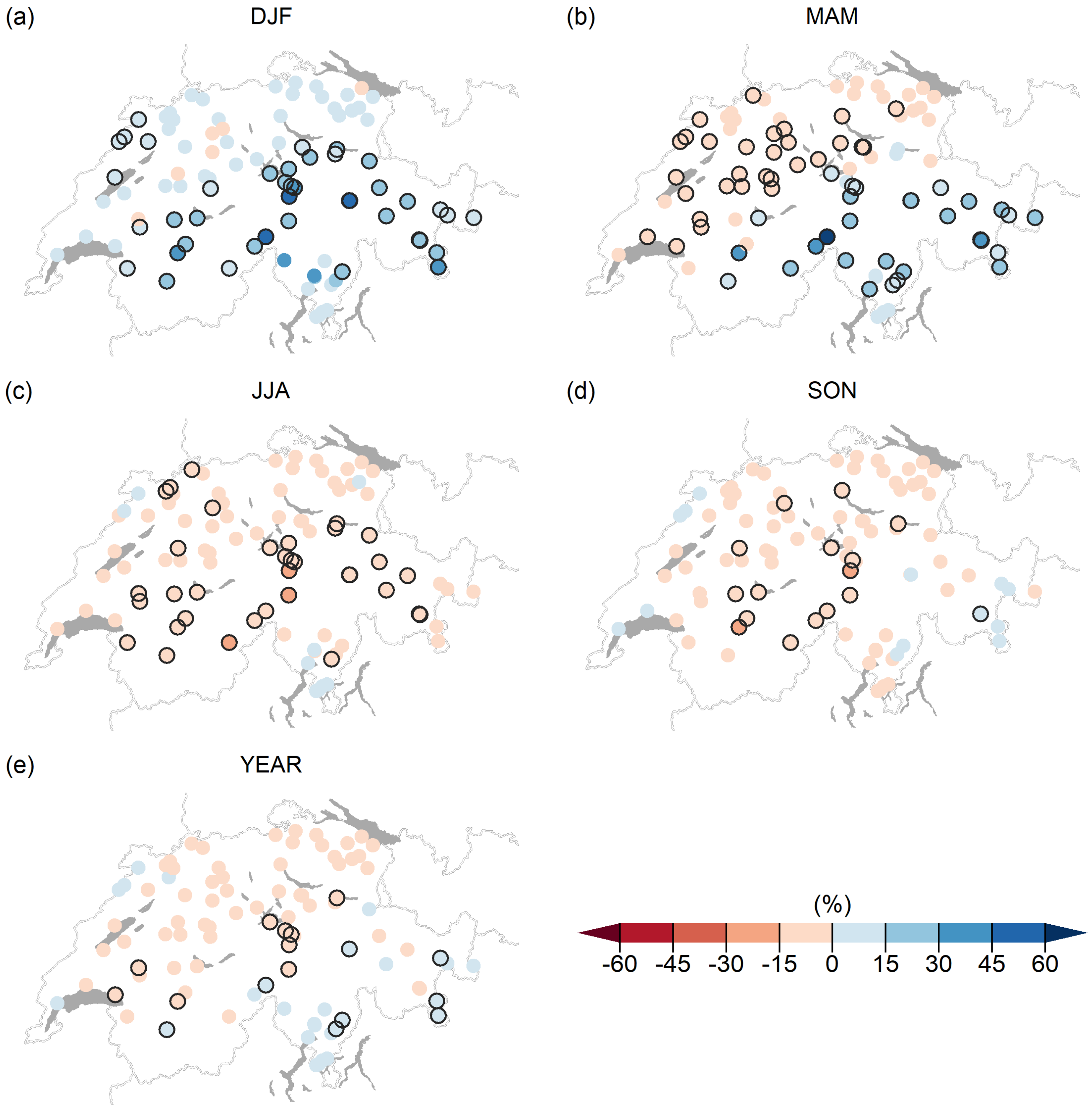

Figure 3: Same as Figure 2 but for RCP2.6

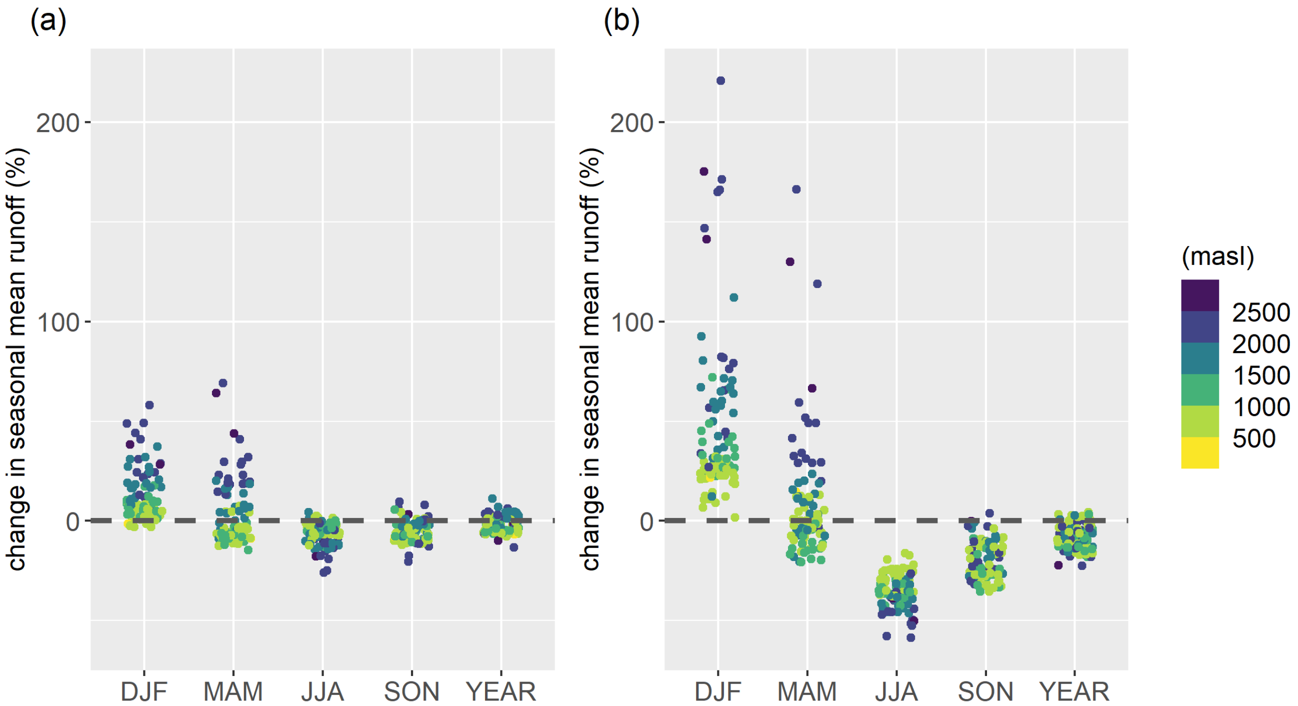

Figure 4: Elevation dependence of the multimodel median (dots) of seasonal and yearly mean changes by 2085 under RCP2.6 (a) and RCP8.5 (b). Colours indicate the mean altitude of the 93 catchments.

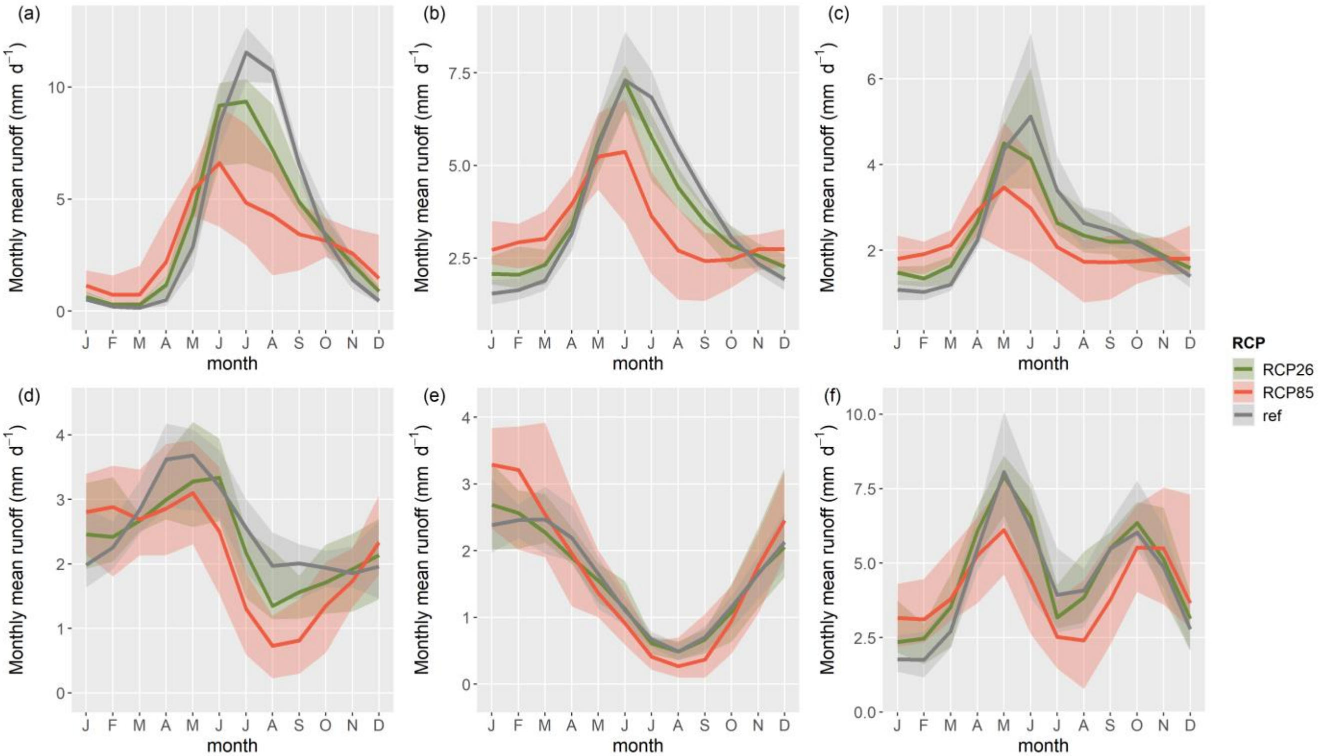

Figure 5: Runoff regimes for the six representative catchments Rosegbach (a), Kander (b), Plessur (c), Emme (d), Venoge (e), and Verzasca (f). Thick lines represent the multi-model median for the reference period (grey), for 2085 under RCP2.6 (green), and for 2085 under RCP8.5 (red). Shadings show the full model range for each RCP.

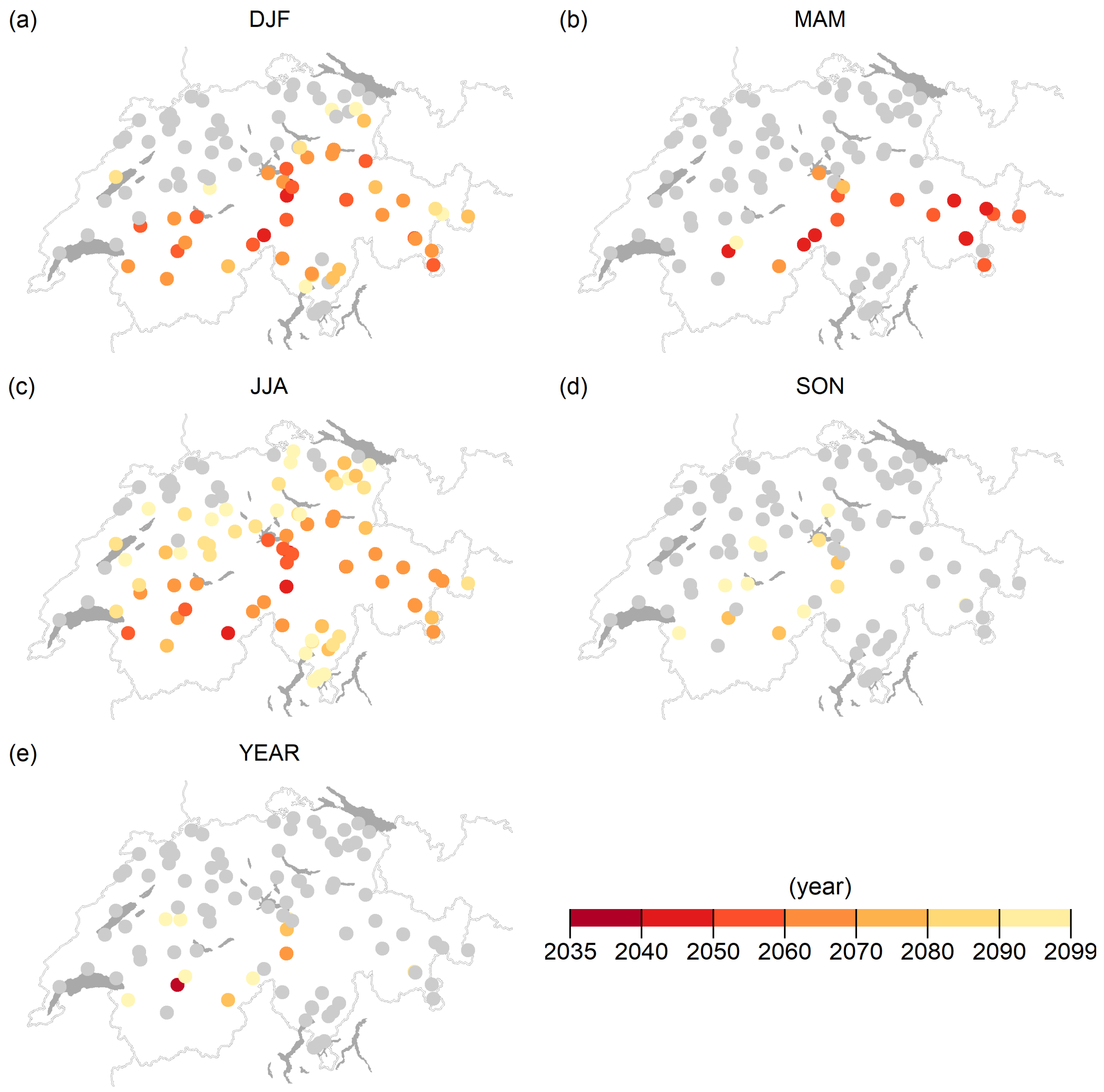

Figure 6: Time of emergence for winter (a), spring (b), summer (c), autumn (d), year (e) when at least 66% of the models agree on significant changes in the distribution of seasonal and yearly means.

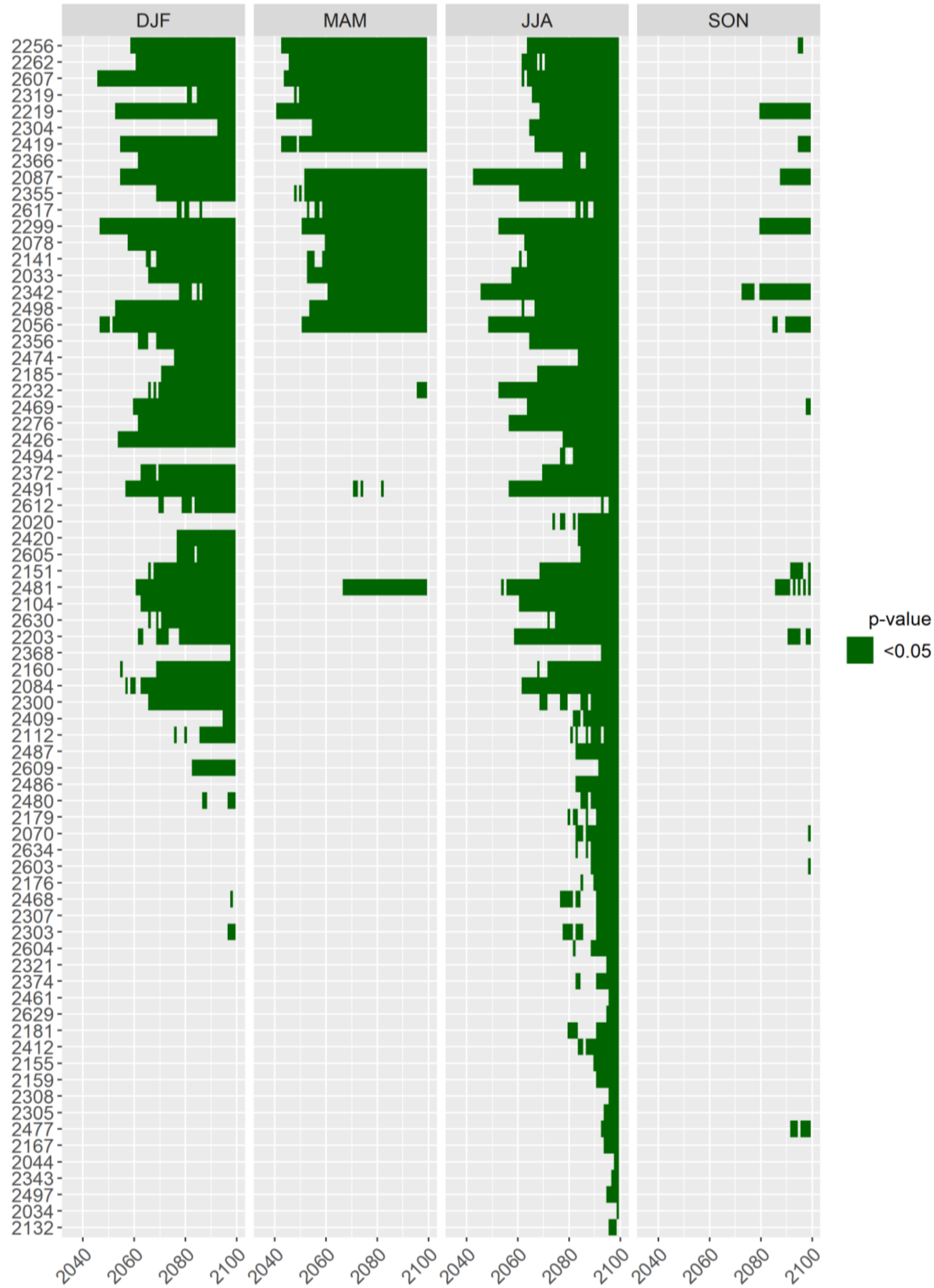

Figure 7: Temporal evolution of time of emergence for the different seasons. Periods where p-value of the Kolmogorov-Smirnov test is lower than 0.05 are highlighted. Only catchments with at least one detection of time of emergence in one of the seasons are shown. Catchments are ordered by mean altitude of the catchment with highest altitudes at the top.

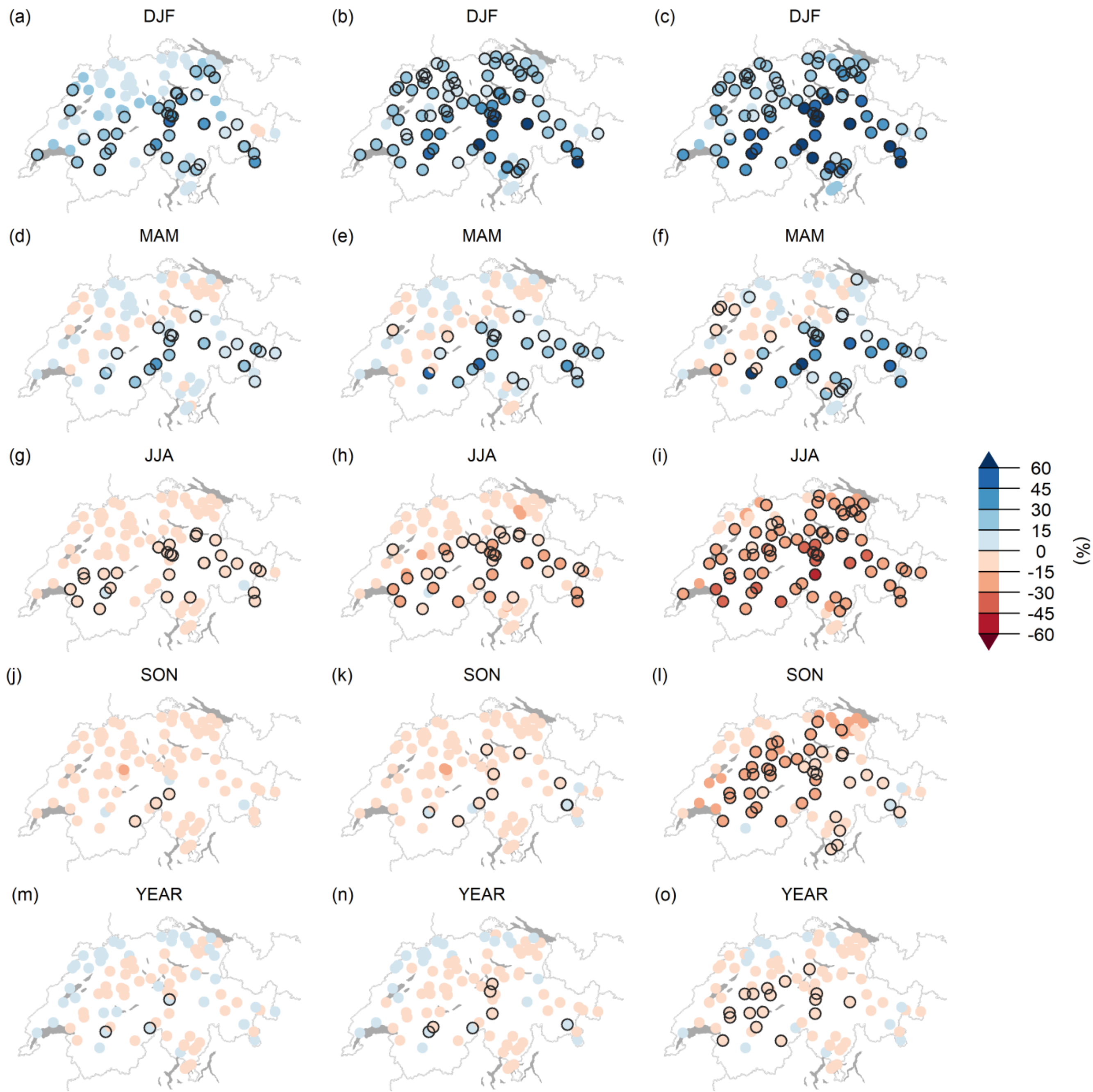

Figure 8: Multimodel median of seasonal and yearly mean changes ~~by~~ +1.5°C (left panels), +2°C (middle panels), and +3°C global warming for winter (a-c), spring (d-f), summer (g-i), autumn (j-l), and year (m-o). Black frames indicate changes with at least 90% model agreement for the direction of change.