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Moderate runoff extremes in Swiss rivers and their seasonal occurrence in a changing climate

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Abstract. Future changes in runoff impact many sectors such as agriculture, energy production, or ecosystems. Therefore, assessments of runoff characteristics under climate change are crucial for decision-makers and water management planners. We study changes in moderate runoff extremes, i.e. low and high flows that occur once every year or season in today's climate. Daily runoff is simulated for 93 Swiss catchments for the period 1981-2099 under the Representative Concentration Pathway 8.5 using 20 downscaled regional climate models from the newest transient Swiss climate change scenarios.

The magnitude of moderate annual low flows is projected to decrease in lower lying catchments and to increase in Alpine catchments. Seasonal low flows in summer are projected to decrease and seasonal low flows in winter to increase. Moderate annual high flows are projected to slightly increase in most catchments but to decrease in high Alpine catchments. However, the climate model agreement on the sign of change in moderate high flows is not robust. The projected decrease in Alpine catchments contradicts results for extreme high flows from previous studies. This difference may be due to different indicators used (moderate extremes vs. extremes). The time of emergence indicates the timing of significant changes in the flow magnitudes. For low flows the time of emergence is early in 21st century in high Alpine catchments due to early changes in winter low flows. In lower lying catchments, significant changes in low flows emerge later in the century. For moderate high flows, only few catchments indicate a significant change.

Shifts in the seasonality of moderate low flows due to climate change are found in many catchments. By end of the 21st century, low flows are projected to occur in late summer and early autumn in most catchments indicating that the lack of precipitation in summer and autumn exceeds the contributions from other processes such as snow and glacier melt contributions. For moderate high flows, changes in seasonality are found in Alpine catchments with a shift towards earlier occurrence in summer due to a reduced contribution of snow and glacier melt in summer. In the projections, low flows occur more frequently in lower lying catchments and less frequently in Alpine catchments. For high flows the frequency increases slightly in most catchments, but models often disagree on the sign of change. Changes in the annual co-occurrence of moderate low and high flows are mainly due to changes in the frequency of low flows that increases in lower lying catchments and decreases in Alpine catchments.

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1 Introduction

Assessments of climate change impacts on hydrology are crucial for future water management and adaptation planning. This is especially true for extreme events, which potentially have severe ecological and societal impacts. In this study, we focus on moderate runoff extremes in both tails of the runoff distribution: moderate annual and seasonal low and high flows. Focusing on moderate extremes is motivated for several reasons. First, moderate extremes are important for water management planning. Second, very extreme floods and very extreme streamflow droughts are difficult to simulate because many processes are not fully understood or not yet resolved in hydrological models. Third, hydrological models are calibrated on observed flow conditions and may miss plausible but unexperienced extreme events. Fourth, climate change projections incorporate large uncertainties regarding small scale extreme events, particularly for extremes in precipitation, which are potential flood triggers. Therefore, we focus on moderate extremes, i.e., events that occur on average once every year or season in today's climate. The larger sample size (number of events) increases the robustness of the estimated changes.

Low flows have a strong impact on water quality, freshwater ecosystems, and human water use such as power production, drinking water production, irrigation for agriculture, fisheries, and recreation (IPCC, 2014). Today, long-term water management planning for Switzerland must rely on low flow assessments from past observations. Since climate change is projected to alter low flow characteristics, low flow projections for the 21st century need to be integrated into water management planning. Changes in low flow indicators in the past decades have been already identified in Europe (Stahl et al., 2010) and in Switzerland (Weingartner and Schwanbeck, 2020). For Switzerland, increasing winter low flows and decreasing summer low flows have been observed in nival (snow-driven) and pluvial (rain-driven) catchments. Low flows in glaciated catchments have increased in all seasons (Weingartner and Schwanbeck, 2020). Previous studies assessed climate change impacts on low flows mainly for macro-scale catchments or regions. Van Vliet et al. (2013) investigated low flow changes on a global scale while other studies focused on European scales (e.g. Feyen and Dankers, 2009; Forzieri et al., 2014; Alderlieste et al, 2014; Papadimitriou et al., 2016; Vidal et al., 2016; Marx et al., 2018). For Switzerland, previous climate impact studies on low flows exist for lower lying catchments in the Swiss Plateau (Meyer et al., 2011), for large-scale catchments (Bernhard and Zappa, 2012), and for very extreme (100-year return periods) low flow regimes in aggregated regions (Brunner et al., 2019). The studies found decreasing low flows in Central Europe but increasing low flows in Alpine areas, where runoff generation is mainly dominated by snow and glacier melt.

High flows may also cause severe damages and significant costs. Hence, potential changes in high flows have to be integrated in water management and infrastructure planning, as well. Assessing future changes in flood magnitude, flood frequency, and flood timing is thus crucial for decision makers. Past events can help to put potential future changes into perspective. Previous studies investigated past trends in floods in Europe (e.g. Stahl et al., 2012; Hall et al, 2014; Mangini et al., 2018; Blöschl et al., 2019; Bertola et al., 2020) and in Switzerland (e.g. Birsan et al., 2005; Allamano et al., 2009; Schmocker-Fackl and Naef, 2010a,b; Castellarin and Pistocchi, 2012). No clear and significant trend in flood magnitude was found in these studies since the studies sometimes disagree on the direction of trends. Various factors make it difficult to compare trends in flood magnitude between catchments and between different studies. The assessments depend heavily on the quality and homogeneity of the observations, the underlying methods such as the selection of indicators or statistical tests, and the investigated time periods. Flood frequencies increased in northern Switzerland and decreased in southern Switzerland in the recent past (Schmocker-Fackl and Naef, 2010a, Blöschl et al., 2019). Periods with many floods were found in the end of the 19th century and after 1968 in northern Switzerland (Schmocker-Fackl and Naef, 2010a). Several assessments of future changes in floods in Switzerland have also been made (Allamano et al., 2009; Köplin et al., 2014; Beniston et al., 2016; Ragettli et al., 2020). Even though those studies differ substantially in methodological aspects and catchment selection, they found in general increasing but not necessarily significant changes in annual runoff maxima under climate change. Seasonal patterns of change were detected with increasing winter floods and decreasing summer floods (Allamano et al., 2009). Also, future shifts in the seasonality of floods depend on the regime type of the catchments (Köplin et al. 2014).

Here we complement these assessments with a focus on moderate low and moderate high flows, i.e. annual or seasonal 7-day runoff minima and daily runoff maxima. The new Hydro-CH2018-Runoff dataset (Muelchi et al., 2020a; Muelchi et al., 2020b in review) is used. It consists of 119-years (1981-2099) long daily runoff simulations driven by the most up to date climate change scenarios for Switzerland CH2018 (CH2018, 2018). For the RCP8.5 emission pathway (Moss et al., 2010; van Vuuren et al., 2011), we analyze (1) changes of moderate low and high flows under climate change, (2) the point in time when significant changes emerge, (3) changes in the seasonality of moderate extremes, and (4) changes in the frequency of their (co-) occurrence. In a companion paper, Muelchi et al. (2020c, in review) assessed changes in runoff regimes and their time of emergence. Here, we extend this analysis with assessments of moderate low and high flows. Since both studies are based on the same simulations (Hydro-CH2018-Runoff ensemble), they complement each other and give a comprehensive overview on hydrological changes in Switzerland. They also complement the above mentioned existing studies on future changes in extreme hydrological events.

2 Data

We analyse daily runoff simulations for 93 medium-sized (14-1700 km^2) catchments distributed in Switzerland and covering a wide range of different runoff regime types including glaciated catchments (22 catchments, glaciation between 0.2-22%), mainly snow driven catchments in the Alpine area, and lower lying catchments mainly driven by precipitation and evapotranspiration. The locations of the catchments are depicted in Fig. 1 with six representative catchments highlighted in green. These representative catchments cover the most important regime types in Switzerland (Weingartner & Aschwanden, 1992): Rosegbach – highly glaciated (22%), Kander – partially glaciated (5%), Plessur –Alpine snow influenced, Emme – pre-Alpine rain and snow influenced, Venoge – lowland rain dominated, and Verzasca – southern-Alpine rain and snow dominated. The data used for the analysis is the Hydro-CH2018-Runoff ensemble consisting of daily mean runoff simulations for each of these 93 catchments (Muelchi et al., 2020a; Muelchi et al., 2020b in review). These simulations were run with the semi-

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distributed hydrological modelling system "PREecipitation-Runoff-EVApotranspiration HRU Model" (PREVAH; Viviroli et al., 2009). PREVAH accounts for important hydrological processes such as evapotranspiration, soil moisture dynamics, snow accumulation, and snow melt. A glacier module was incorporated to account for glacier melt in glaciated catchments. PREVAH was calibrated (even years between 1985-2014) and validated (uneven years between 1985-2014) for each of the 93 catchments individually. Using observed discharge for calibration may put too much emphasis on high flow conditions and potentially overestimates low flow conditions. Therefore, the calibration was simultaneously performed on four observational groups: observed daily discharge measurements, inverted daily discharge, monthly mean runoff, and the annual volume. This ensures good performance for the general catchment response to meteorological forcing as well as for the discharge volume. Also low flows are represented in a satisfactory performance. The hydrological model is driven with daily temperature and precipitation data from the new high resolution (2 by 2 km) climate change scenarios for Switzerland CH2018 (CH2018, 2018) for each catchment separately. In non-glaciated catchments the land use was assumed to be constant over the simulation period. In glaciated catchments, the glaciated area was updated every 5 years in line with glacier projections by Zekollari et al. (2019) that were driven by the same climate model chains. Land use in areas where glaciers disappear during the simulation period were replaced by bare soil for areas below 3000 masl and by rock for areas above 3000 masl. The Hydro-CH2018-Runoff ensemble includes simulations for three different emission pathways: RCP2.6, RCP4.5, and RCP8.5. Because the number of available simulations per emission scenario differs, we constrained our analysis to the RCP8.5 pathway (Moss et al., 2010; van Vuuren et al., 2011) where the largest number of simulations is available. In total, 20 daily simulations under the RCP8.5 emission pathway for the period 1981-2099 are available for each of the 93 catchments. Table 1 shows the climate model combinations used in this study.

3 Methods

The analysis focuses on moderate low flows and moderate high flows. Several indicators for low flow analysis exist focusing on different properties of low flows (Tallaksen and Van Lanen, 2004). For low flow we use the minimum 7-day moving average runoff (MAM7) within an extended season or a year. This indicator is proposed by the Swiss Federal Office for the Environment (FOEN) for low flow statistics. The 30-year average of MAM7 is then considered as moderate low flow and used to assess changes in moderate low flows under climate change. For moderate high flows, we use the 30-year average of the annual maxima per extended season or year as moderate high flow indicator. The seasons are defined as extended summer (May to October) and extended winter (November to April) season. The seasonal distinction is motivated by the fact that winter and summer low flows are governed by different processes and that they have different impacts. The indicators for the annual time window will be referred to as moderate low and moderate high flows while the indicators for the extended winter season and extended summer season will be referred to as the lowest and highest seasonal flows, respectively.

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Percent changes are calculated as the relative difference between the 30-year mean of the future period (2070-2099) and the 30-year mean in the reference period (1981-2010) for each simulation. The multi-model median of the relative changes by end of the century is regarded as the best estimate. To get an indication of the robustness of the projected changes, catchments are highlighted in the Figures when at least 90% of the simulations show the same direction of change (positive or negative).

To evaluate potential changes in the seasonality the day of the year for each event (low flow and high flow) is extracted. Since moderate low flows are calculated from 7-day averages, the last day of the 7-day period is considered as day of low flow event. Median seasonality is then derived by transforming the day of the year into angular values and by applying circular statistics. Finally, the angular values are transformed back to the day of the year.

To assess when significant changes in the distribution of moderate low and high flows occur, the time of emergence is used (Mahlstein et al., 2011). For each simulation, moderate low and high flow magnitude distributions of moving 30-year windows are tested against the 30-year reference period using the Kolmogorov-Smirnov test. The time of emergence is then defined as the last year of the first 30-year moving window where the Kolmogorov-Smirnov test is rejected with a p-value lower than 0.05 (95% significance). We highlight the time of emergence when at least 66% of the models detect a significant change in the same 30-year window for the first time. Note that the time of emergence may not necessarily be stable over time.

Changes in the frequency of moderate low and high flows are quantified by counting years when a pre-defined runoff threshold is exceeded or undercut. We use the median magnitude of moderate low and high flows in the reference period as threshold. For moderate high flows we count years with high flows exceeding this threshold. For low flows we consider years with low flows below the threshold. This was done for each seasonal and annual time window and each simulation separately. Finally, the percentual change in occurrence is calculated. We also investigate the co-occurrence of moderate low and high flows. Co-occurrence is considered when high flows exceeding the reference threshold and low flow undercutting the reference threshold occur in the same time window (year, extended winter, extended summer).

4 Results

4.1 Future changes in moderate low flows

Median seasonal occurrence of moderate annual low flows is shown in Fig. 2 for the reference period (Fig. 2a) and by end of the century (Fig. 2c). In Alpine catchments, annual low flows occur in late winter or early spring in the reference period. By end of the century, low flows occur in autumn. However, low flows in very high Alpine catchments do not change their seasonality. Median seasonal occurrence of low flows in pre-Alpine catchments shifts from late autumn to early autumn. In southern Alpine catchments, low flows change their median seasonal occurrence from winter and spring to early autumn. No clear change in seasonality is found for lower lying catchments with low flows occurring in late summer and early autumn. Despite in very high Alpine catchments low flows occur between August and October by end of the century.

The moderate annual low flows show distinctly different patterns of change in magnitude for Alpine and non-Alpine catchments (Fig. 3 left panels). Please note that the scale bar is limited to -60% and +60% for readability. While the annual low flows (Fig. 3a) decrease by up to -66% in most of the lower lying catchments (68 out of 93 catchments in total), the Alpine catchments (25 catchments with mean altitude above 1500 masl) show strong increases (up to +200%). Lowest winter flows in Alpine catchments coincide with the typical low flow season in the reference period while lowest summer flows in coincide with the typical low flow season in lower lying catchments. Lowest winter flows increase on average by +22%. An increase is found in two thirds of the catchments, again with stronger increases in very high Alpine catchments (Fig. 3c). In summer, the lowest flows decrease on average by -40% (maximum decrease -74%) (Fig. 3e). However, three high Alpine catchments still show an increase in lowest summer flows due to an increase in lowest flows in late spring (May). The model agreement (>90%) is stronger in summer (87 catchments) than in the annual (63) and winter (30) low flows.

Transient changes of moderate low flow intensity and seasonality throughout the 21st century for three representative Alpine catchments and three representative lower lying catchments are shown in Figs. 4 and 5, respectively. The relative changes for each of the catchments and each of the time windows are summarized in table 2. The high Alpine catchment Rosegbach is highly glaciated in the reference period with a glacier coverage of 22% but loses most of the glacier coverage by end of the century (glacier coverage: 1%; not shown). The catchment shows strong increases in annual low flows and lowest seasonal flows (Fig. 4 top row). While the seasonality of the annual low flows and lowest winter flows does not change, the occurrence of lowest summer flows shifts from early summer to autumn. This indicates a change in the underlying processes leading to lowest summer flows: In the reference period, the retention of water in snow in ice still takes place in May. Under climate change, enhanced snowmelt increases runoff in early summer. Towards the end of the century, the contribution of snow and glacier melt in summer decreases. At the same time, precipitation in summer will decrease. This leads to a strong decrease in summer runoff. The combination of increasing runoff in early summer and decreasing runoff in late summer and early autumn results in a shift of lowest summer flows from early summer to early autumn. In the catchment Kander with only little glacier influence (Fig. 4 middle row), the annual low flows and lowest winter flows increase mainly due to enhanced winter precipitation falling as rain instead of snow. Lowest summer flows decrease by end of the century. The annual low flows and lowest seasonal flows occur earlier by end of the century. The nival catchment Plessur shows a strong shift in seasonality in the annual low flows from winter to autumn but no change in the magnitude of low flows (Fig. 4 bottom row). Lowest winter flows increase and occur earlier in the season while the lowest summer flows decrease but do not change seasonality. The annual low flows and lowest seasonal flows decrease by end of the century in the pre-Alpine snow and rain influenced catchment Emme. The annual low flows show a clear shift in seasonality from late autumn/early winter to early autumn (Fig. 5 top row). A shift towards earlier occurrence is also found for lowest winter flows but not for the lowest summer flows. In the mainly rain and evaporation driven catchment Venoge, the annual low flows and lowest summer flows do not change their seasonality, but lowest winter flows tend to occur earlier in the season (Fig. 5 middle row). The magnitude of annual low flows and lowest seasonal flows decrease. The southern Alpine catchment Verzasca shows a decrease in the magnitude and a strong

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shift in occurrence from late winter to early autumn for annual low flows (Fig. 5 bottom row). Lowest winter flows increase while lowest summer flows decrease, both without change in the seasonality.

Figure 6 (left panels) shows the time of emergence for moderate low flows and lowest seasonal flows when at least 66% of the models show significant changes in the distribution. 43 catchments show a time of emergence for annual low flows with particularly early significant changes in glaciated and/or high Alpine catchments (earliest 2018-2047). The 20 catchments showing a time of emergence in lowest winter flows have a mean altitude higher than 1600 masl. In summer, 80 catchments show significant changes in lowest flows with an early time of emergence again found in high Alpine catchments, but also lower lying catchments show a time of emergence later in the century.

4.2 Future changes in moderate high flows

The median seasonal occurrence of annual high flows is shown in Fig. 2 for the reference period (Fig. 2b) and by end of the century (Fig. 2d). In Alpine catchments, the median seasonal occurrence shifts from summer to late spring and early summer. However, highly glaciated catchments do not change their high flow seasonality. Moderate high flows in pre-Alpine catchments occur in spring in the reference period and in winter in future. A change in seasonality is also found in southern Alpine catchments where high flows shift from late summer and early autumn to late autumn in future. In lower lying catchments, no change in high flow seasonality is found.

Relative changes of magnitude for moderate high flows by end of the century are depicted in Fig. 3 (right panels). The 30-year means of annual high flows (Figure 3b) increase in 71 catchments (up to +28%) and decrease in 22 catchments (up to -22%). Compared to the changes in moderate low flows, the magnitude of change in high flows is smaller. There are no clear spatial patterns or elevation dependences and good model agreement (>90%) is only found in 12 catchments. Highest winter flows in lower lying catchments coincide with the typical high flow season in the reference period, while highest flows in higher elevation catchments are mainly found in the summer half year. Highest winter flows increase in all catchments and model agreement is higher with 45 (out of 93) catchments showing a good agreement (Fig. 3d). Strongest increase in magnitude and good model agreement are found in high Alpine catchments. However, highest winter flows in high Alpine catchments are still small in magnitude. Highest winter flows in the lower lying catchments increase only moderately and model agreement is generally weak. Highest summer flows (Fig. 3f) decrease in 74 catchments (up to -26%) and increase in 19 catchments (up to +15%). Strongest reductions in highest summer flows are found in high Alpine catchments including the only six catchments showing good model agreement. A spatial cluster of increasing highest summer flows is found in the Jura mountains (north-west Switzerland).

Annual high flows and highest summer flows in the Rosegbach catchment decrease towards the end of the century and tend to occur earlier in summer while highest winter flows increase and occur more often later in the season (Figure 7 top row). A similar pattern is also found for the Plessur (Figure 7 bottom row). In the Kander, the annual high flows increase slightly and shift to earlier in the year and can also occur in winter by end of the century (Figure 7 middle row). Also, highest winter flows in the Kander increase, and highest summer flows show a small decrease without a significant shift in the occurrence. The high

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flows in the Emme and the Verzasca do not change their seasonality but highest winter flows increase and highest summer flows decrease (Fig. 8 top and bottom rows). The pluvial catchment Venoge shows increasing moderate annual high flows and seasonal highest flows with no change in the seasonality (Fig. 8 middle rows).

The time of emergence of moderate high flows is depicted in Fig. 6 (right panels). Compared to moderate low flows, there are fewer catchments exhibiting significant changes and these catchments are mostly high Alpine catchments. For annual high flows, three high Alpine (>2000 masl) catchments show a time of emergence with earliest time of emergence of 2078 (2049-2078). The 27 catchments showing significant changes in highest winter flows (earliest 2044, 2013-2044) are also located in the Alpine ridge (>1500 masl mean altitude). In summer, only six catchments (>1800 masl) show a time of emergence and the earliest time of emergence is 2071 (2042-2071).

4.3 (Co-)occurrence of low and high flows

So far we have assessed changes in the magnitude and seasonality of low and high flows, in this section we address changes in frequency and the co-occurrence of high and flow events. For this we need to set a threshold to identify events. The threshold discharge value is defined as a value occurring every second year in the reference period (i.e., median in the reference period). Figure 9 illustrates relative changes in the occurrence of low flows (Fig. 9 a-c) and high flows (Fig. 9 d-f) by end of the century (2070-2099) that fall below resp. exceed median values. For annual low flows, the occurrence of low flow events increases in 70 catchments. These catchments are mainly found in rain dominated areas and to a lesser extent also in snow dominated areas. Catchments showing fewer occurrences are only found in high Alpine areas. Good model agreement is found in 56 catchments. Lowest flows occur also more often in summer (sometimes occurring every year) in almost all regions except few very high elevation catchments. Most of the catchments (82) show a good model agreement on the increase of lowest summer flow occurrence. Lowest winter flows tend to occur less often in mountainous areas while lower lying catchments still show an increase in occurrence. However, only mountainous catchments show good model agreement.

Changes in the occurrence of high flows are less clear than for low flows. For annual high flows, 58 catchments show increasing occurrences, and 30 catchments show decreasing occurrences. However, the changes are often small. Also, no clear spatial or elevation pattern emerges and model agreement is weak. For the highest winter flows, all catchments will face more years with more frequent high flow events than today, particularly in the high Alpine regions. In contrast, the occurrence of highest summer flow events will decrease by end of the century in most catchments. Model agreement is weaker in summer than in winter.

Figure 9 (g-i) shows changes in the co-occurrence of moderate high and low flows defined as the occurrence of a high flow event and a low flow event in the same time window. Annual co-occurrence increases in most catchments, particularly in the lower lying catchments. In high Alpine catchments, this co-occurrence decreases mainly due to the strong increase in winter runoff. Winter co-occurrence decreases mainly in high altitude catchments but also in few of the lower lying catchments. In summer, most catchments (85 catchments) show increasing co-occurrence by end of the century. Only 8 high Alpine

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catchments show decreasing co-occurrence. In contrast to high flow occurrence, the model agreement is stronger in summer (48) than in winter (14) co-occurrence.

5 Discussion

5.1 Changes in moderate low flows

Low flows in Alpine regions typically occur in winter and early spring when precipitation falls as snow and accumulates. The storage as snow limits the direct runoff and only little runoff (baseflow) occurs in winter. Since higher temperatures result in both a change of the precipitation type (more precipitation falls as rain instead of snow) and an enhancement of earlier snow melt, the lowest winter flows are projected to increase in the future. Also, the seasonal occurrence shifts from late winter to late autumn. This shift indicates that snow storage no longer dominates low flows, but summer drought in combination with lack of snow and glacier melt becomes the main driver of low flows. However, this is not the case in highly glaciated catchments with very high mean altitudes, where the seasonality of low flows does not change. Considering the summer half year, the lowest summer flows in Alpine catchments decrease due to the combination of decreasing summer precipitation, enhanced evapotranspiration and the reduced contribution of snow and glacier melt to the runoff. An exception are catchments in very high altitudes, which show increasing lowest summer flows by end of the century. Increasing lowest winter flows in Alpine areas have been identified in observations (Weingartner and Schwanbeck, 2020) and our results show that this trend continues with climate change. The findings are also in agreement with results for projections of very extreme low flow regimes (100-year return period, Brunner et al., 2019).

In the present climate, low flows occur mostly in late summer and autumn in lower lying catchments. In these catchments runoff volumes during low flow conditions are projected to decrease in all time periods, with the reduction in the summer half year being much stronger than in the winter half year. The reasons for the reduction in summer are the decreasing summer precipitation and the higher temperatures enhancing evapotranspiration. The projected lowest summer flow reduction is in line with observed trends (Weingartner and Schwanbeck, 2020) but the changes get amplified under climate change. Even though the climate change scenarios project increasing winter precipitation, the lowest winter flows decrease mainly due to a shift in the occurrence from winter to late autumn. The seasonality of annual low flows does not change in mainly rainfed catchments. In pre-Alpine regions, the seasonality of annual low flows shifts from late autumn to early autumn.

In the snow- and rain-driven southern Alpine regions, there are typically two periods of low flows: one in late summer and one in winter, with the winter minimum often being lower in the reference period. Under climate change, the seasonal occurrence of low flows shifts from winter to late summer and early autumn. At the same time, runoff in low flow situations decreases by end of the century.

Increasing lowest winter flows in Alpine regions may be beneficial for energy production, but the decreasing lowest summer flows may have severe impacts in agricultural regions where water is needed for irrigation. Also, the decreasing water

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availability during low flows may have implications on the cooling of infrastructures and in combination with increasing water temperatures may foster water stress for ecosystems.

5.2 Changes in moderate high flows

In Alpine areas moderate annual high flow and highest summer flows will decrease in the projections. This can be explained by the decreasing contribution of melt water together with decreasing summer precipitation and enhanced evapotranspiration. In future, Alpine areas will face about half of the present mean runoff in summer (Muelchi et al., 2020c in review). This decrease is also reflected in moderate high flows. This is in contrast to the highest winter flows which are projected to increase with climate change. However, highest winter flows are still smaller in magnitude than highest summer flows. Decreases in the runoff volume during highest summer flows and increases in highest winter flows were also found by Allamano et al. (2009) for mountainous regions. However, the decreasing annual high flows in Alpine areas contradict the results of Köplin et al. (2014), who found increasing high flows in the Alpine area. The reason for the different results is not conclusively clear, but in Köplin et al. (2014) very extreme floods are considered, while this study considers moderate high flows.

Annual high flows in the Alpine region usually occur in summer, when the snow line is high, melting processes are in progress, and precipitation intensities are largest. In glaciated catchments, high flows occur at the end of summer when glacier melt reaches its peak in the reference period. In snow influenced catchments today, the high flows tend to occur in early summer during the snowmelt. In both regime types, seasonal occurrence is shifted to earlier months such that the high flows occur earlier in summer in future. An exception are highly glaciated catchments with high mean elevation, which will also have snow and glacier influence in summer in the future. In these catchments, the seasonal occurrence hardly changes. Köplin et al. (2014) also found shifts in the occurrence of extreme floods in Alpine areas. Their results show a shift in nival catchments from summer to autumn, whereas our results show a shift to earlier spring and early summer.

In lower-lying areas annual high flow and highest winter flows tend to increase, although the increase is often not robust across models. In summer, the highest flows tend to decrease again with no robust signals across models. Moderate high flows occur in winter in pluvial catchments and this will not change in future. In catchments partly influenced by snow, where high flows occur in spring, the sesasonal occurrence is shifted from spring to late winter. This behavior is in agreement with the results of Köplin et al (2014). In the southern Alpine areas, the annual high flows also tend to increase and will shift from late summer and early autumn to late autumn, which was also found by Köplin et al. (2014) for extreme floods.

The increased water availability in winter in Alpine regions may be beneficial for energy production. But increasing high flows in mainly lower lying catchments may increase the potential of flood damages. However, this increase is not robust among the climate models and moderate high flows only partially reflect severe floods.

5.3 Time of emergence of significant changes

Significant and robust changes in the magnitude of moderate low flows emerge mainly for annual low flows and lowest summer flows. The majority of the catchments show a significant change in magnitude for summer low flows. High Alpine catchments

show earlier significant changes in lowest summer flows than lower lying catchments. Early times of emergence in high Alpine catchments were also found for summer mean flow in Muelchi et al. (2020c in review). In winter, only Alpine catchments show a significant change in lowest winter flows. The main reason for this are snowpack related processes like the change in precipitation type (snow vs. rain) together with smaller snow accumulations and associated enhanced direct runoff.
The magnitude of high flows significantly changes only for few catchments. This is due to the large variability across the climate models. To detect a time of emergence, we require that at least 66% of the models agree on significant changes in the distribution of high flows.

5.4 Changes in the (co-)occurrence of low and high flow events

The frequency of annual moderate low flow events increase in lower lying catchments, while fewer low flows events are detected in Alpine catchments. However, the frequency of the lowest summer flows will increase in almost all catchments. In some catchments, the frequency almost doubles. This may have implications in agricultural areas where irrigation plays an important role. High flow events in winter will occur more often, while summer high flow events will occur less often. A clear pattern in occurrence of annual high flow events is not detectable because model agreement is weak. However, most catchments show a tendency towards more occurrences. Co-occurrence of low and high flow events in the same year increases in most lower lying catchments. In contrast, high elevation catchments show a decreasing co-occurrence mainly due to the increase in low flows. The changes in co-occurrence are dominated by changes in low flow occurrence. Since low flows in lower lying (high Alpine) catchments tend to occur much less (more) often, co-occurrence also decreases (increases). Co-occurrence of high and low flow events in the same extended season are important for ecosystems since the recovery time may be shortened. Information about the co-occurrence is also important for insurance companies for their risk assessments.

5.5 Uncertainties

Uncertainties in our results are larger for moderate high flows than for moderate low flows. The larger uncertainties in high flows are due to several reasons. First, high flows are difficult to model since many different processes interact with each other. In particular, small-scale precipitation patterns have a strong influence on high flows and the input data from the climate models does not reflect small-scale precipitation processes well (Ban et al., 2015). Second, the uncertainty arising from internal variability of extreme precipitation is large and is thus also reflected in our results. Third, our results represent 30-year averages as well as averages across models. Therefore, a lot of information is averaged out. Other sources of uncertainty also affect our results such as the climate models and their boundary and initial conditions, the post-processing method, the hydrological model and its calibration, and the underlying glacier projections.

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6 Conclusions

We assessed changes in moderate low and high flows (annual and seasonal flow maxima and minima) for 93 catchments in Switzerland under climate change. Runoff simulations were driven by the newest transient climate change scenarios (CH2018) for Switzerland for 1981-2099 based on the RCP8.5 scenario. This study analyzes not only changes in the magnitude of moderate low and high flows but also on changes in their seasonal occurrence and their frequency. Thanks to the transient property of the simulations, also the timing of significant changes (time of emergence) could be assessed.

The projections indicate the following results. For low flows, a strong elevation dependence of the changes over time was found. While low flow magnitudes decrease in lower lying catchments, they increase in Alpine catchments extending observed trends in the past (Weingartner and Schwanbeck, 2020). Low flows decrease by -40% in summer, and increase by +22% in winter. The results for low flow magnitudes are in line with projections of previous studies (e.g. Meyer et al., 2011; Bernhard and Zappa, 2012; Brunner et al., 2019). A shift in seasonality was found for most of the catchments. By end of the century, low flows will occur predominantly in late summer and autumn in most of the catchments. This indicates that the lack of precipitation in summer exceeds the contribution of other processes such as snow and glacier melt contributions. The pronounced projected decrease in summer low flows in most of the catchments (except some high Alpine catchments) may become one of the most important challenges in terms of water management. In contrast, increasing winter low flows in Alpine catchments may be beneficial for hydropower production.

For moderate high flows, relative changes are smaller than for low flows. Most of the catchments show an increase in moderate high flows but the model agreement on the changes is not robust with the exception of a few catchments in northern Switzerland and the Jura mountains. High Alpine catchments show a decrease in the highest summer flows, mainly due to reduced melt water in future, and an increase in the highest winter flows. The magnitude of winter high flows in Alpine catchments is much smaller than for summer high flows. Thus, the increasing winter high flows are not that important from a hydrological point of view but may become relevant for ecosystems. Projected changes in magnitude and shifts in seasonality of moderate high flows in lower lying catchments are in line with previous studies (e.g. Koeplin et al., 2014; Brunner et al., 2019). For Alpine catchments, our results do not agree with other projections in terms of magnitude and in some cases in terms of seasonality. This contradiction may arise due to the different indicators considered. While our study focuses on moderate high flows, the other studies focused on extreme high flows, which can be governed by different processes than moderate high flows.

Significant changes in the magnitude of low flows emerge early in the 21st century for high Alpine catchments because of an increase in winter flows. For many lower lying catchments a significant decrease in summer low flow magnitude is detected but later in the 21st century. Changes in the magnitude of high flows are mostly not robust across climate models and thus not significant.

Low flow events will occur more often in lower lying catchments and less often in high Alpine catchments. Like the weak signal in the magnitude of high flows, also changes in the occurrence of high flow events are small. However, most of the catchments will experience an increasing frequency in the occurrence of high flow events. An elevational pattern was found

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for the co-occurrence of moderate low and high flow events, with increasing co-occurrence in lower lying catchments and decreasing co-occurrence in high Alpine catchments. This pattern is dominated by changes in the frequency and magnitude of moderate low flows.

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Data availability

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

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: Overview of the available climate model chains and their initial grid spacings of 12 km (EUR-11) and 50 km (EUR-44).

Global Climate Model	Regional Climate Model	EUR-11	EUR-44
ICHEC-EC-EARTH	KNMI-RACMO22E		X
	DMI-HIRMAM5	X	
	CLMcom-CCLM4-8-17	X	
	CLMcom-CCLM5-0-6		X
	SMHI-RCA4	X	
MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	X	
	CLMcom-CCLM5-0-6		X
	KNMI-RACMO22E		X
	SMHI-RCA4	X	
MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	X	
	CLMcom-CCLM5-0-6		X
	SMHI-RCA4	X	
	MPI-CSC-REMO2009-2	X	
MIROC-MIROC5	CLMcom-CCLM5-0-6		X
	SMHI-RCA4		X
CCCma-CanESM2	SMHI-RCA4		X
CSIRO-QCCCE-CSIRO-Mk3-6-0	SMHI-RCA4		X
IPSL-IPSL-CM5A-MR	SMHI-RCA4	X	
NCC-NorESM1-M	SMHI-RCA4		X
NOAA-GFDL-GFDL-ESM2M	SMHI-RCA4		X

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Table 2: Relative changes (in %) by end of the century and the seasonal occurrence (OCC) of moderate low and high flows for the six representative catchments. The seasonal occurrence indicates the season where the moderate flow extremes occur most frequently. Abbreviations: Seasonal occurrence in winter in the reference period and predominantly in summer in the future period (WS), seasonal occurrence in the winter in both periods (WW), seasonal occurrence in summer in the reference period and in winter in the future period (SW), and seasonal occurrence in summer in both periods (SS).

Catchment	Moderate low flows				Moderate high flows			
	YEAR	WINTER	SUMMER	OCC	YEAR	WINTER	SUMMER	OCC
Rosegbach	+191%	+199%	+89%	WW	-20%	+97%	-25%	SS
Kander	+20%	+41%	-37%	WW	+8%	+50%	-5%	SS
Plessur	-1%	+32%	-43%	WS	-10%	+43%	-14%	SS
Emme	-53%	-17%	-66%	WS	+2%	+13%	-7%	SW
Venoge	-45%	-16%	-47%	SS	+22%	+25%	+4%	WW
Verzasca	-22%	+42%	-53%	WS	+6%	+24%	-3%	SS

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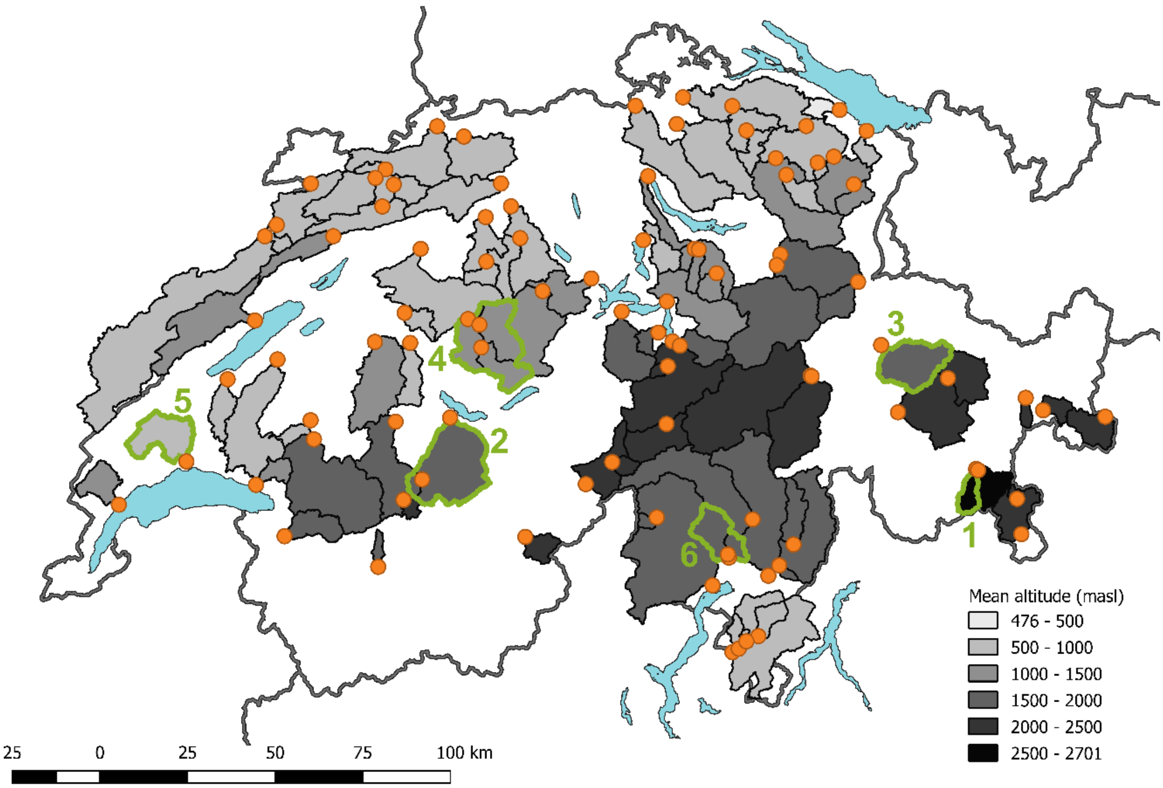

Figure 1: Overview of the study region and the location of the gauging stations (orange dots). Shadings indicate mean altitude of the respective catchment. Green contours indicate the six example catchments: Rosegbach – Pontresina (1), Kander – Hondrich (2), Plessur – Chur (3), Emme – Emmenmatt (4), Venoge – Ecublens (5), Verzasca – Lavertezzo (6). (from Muelchi et al., 2020c in reivew)

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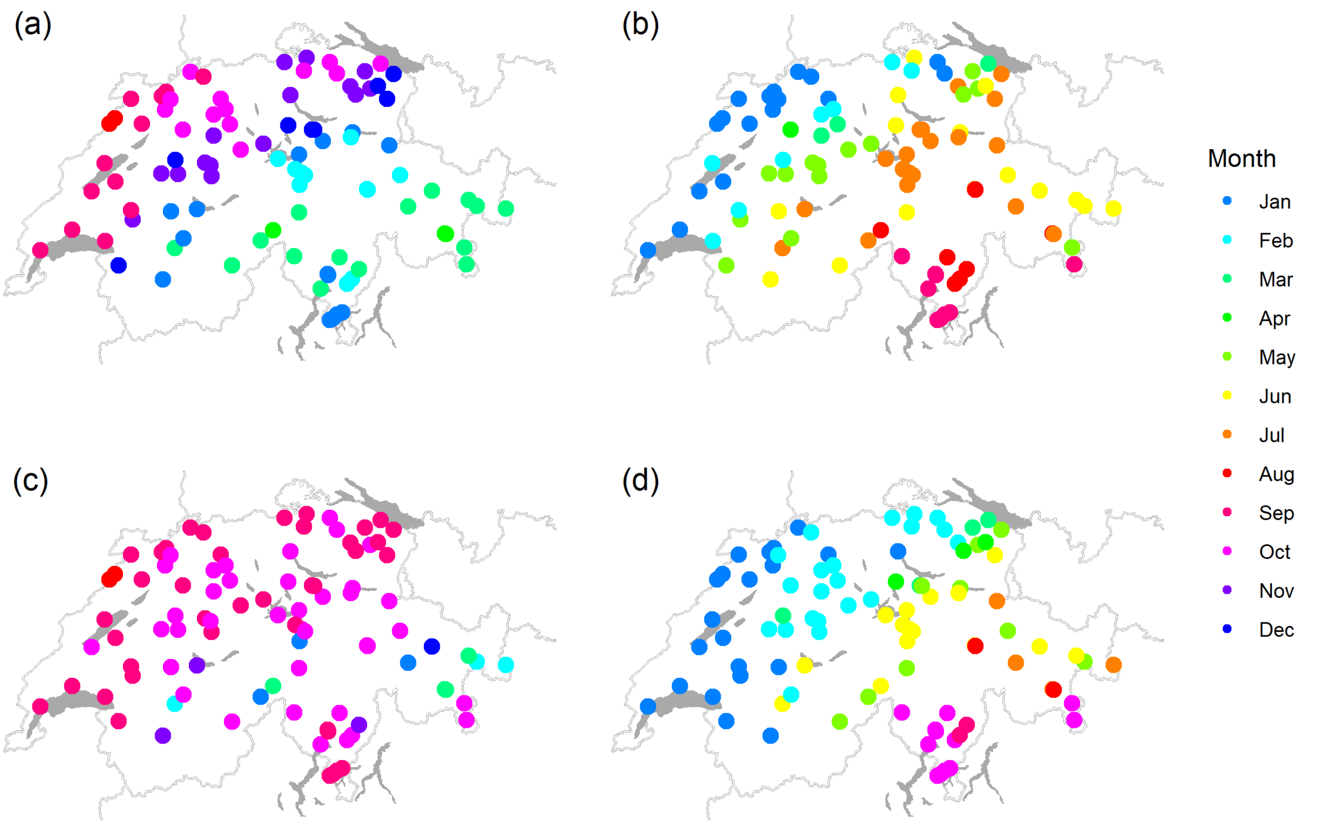
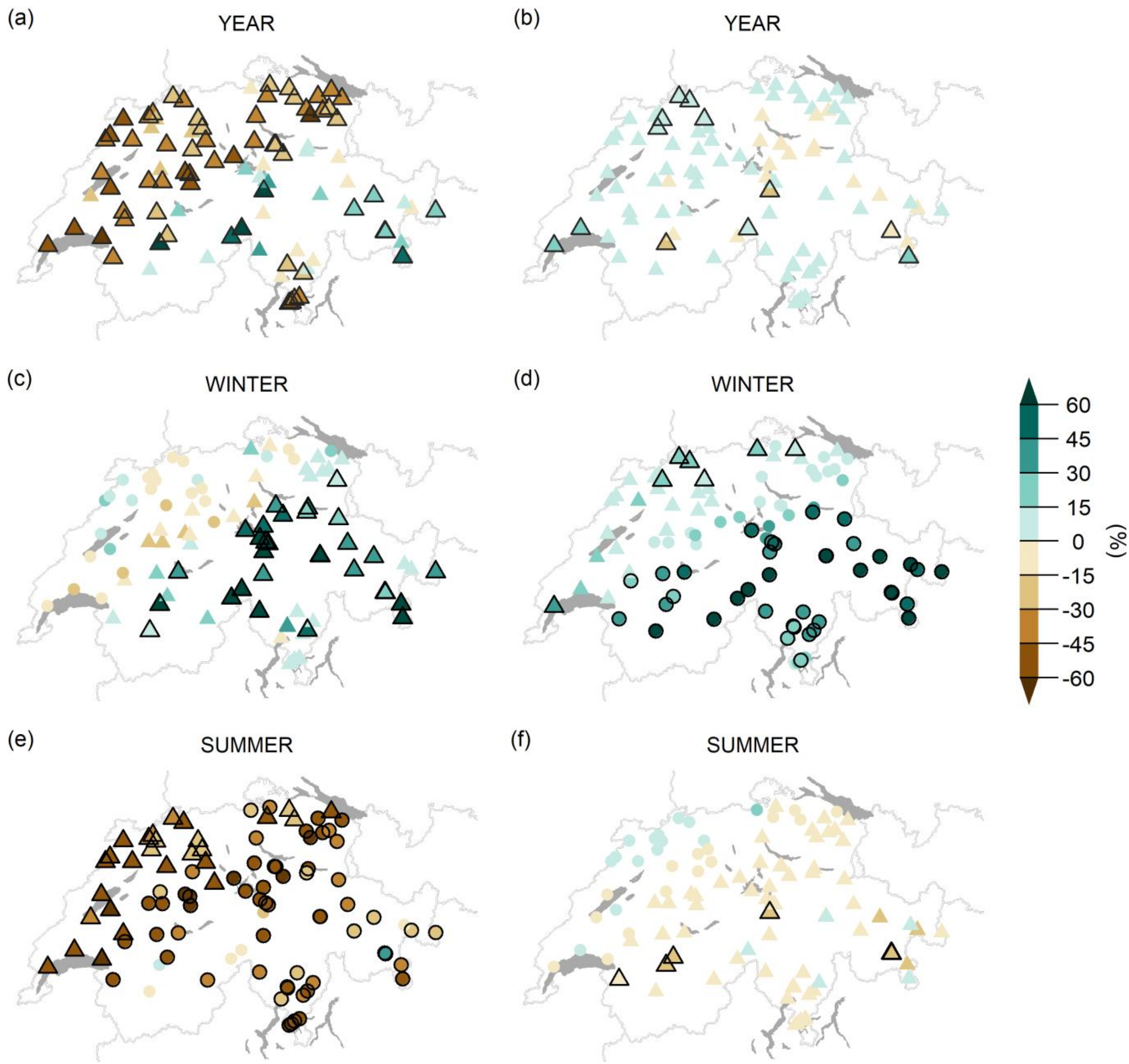


520 **Figure 2: Median monthly occurrence of moderate low flows (left panels) and high flows (right panels) for the reference period (1981-2010, a,b) and end of the century (2070-2099, c, d).**



525 **Figure 3: Relative changes of magnitude by end of the century for moderate low flows (left panels) and moderate high flows (right panels) for the year (a,b), winter (c,d), and summer (e,f). Triangles indicate catchments with annual moderate low and high flows occurring in the respective time window in the reference period. Circles indicate seasonal lowest and highest flows outside the typical low and high flow season. Black contours indicate changes with at least 90% of the models agreeing on the direction of change.**

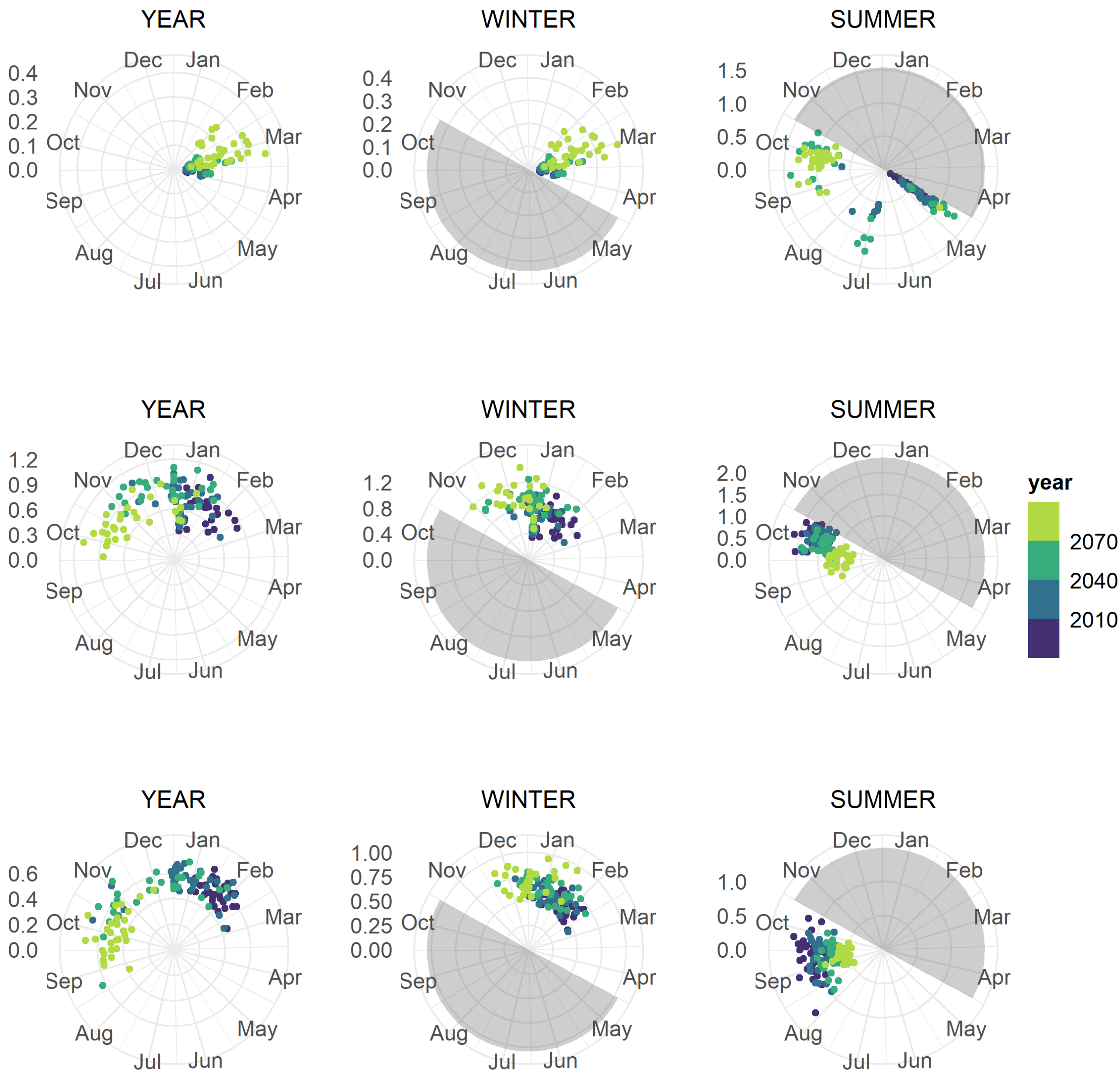


Figure 4: Multi-model median of intensity and seasonal occurrence of low flows and seasonal lowest flows in Alpine catchments: Rosegbach (top row), Kander (middle row), and Plessur (bottom row).

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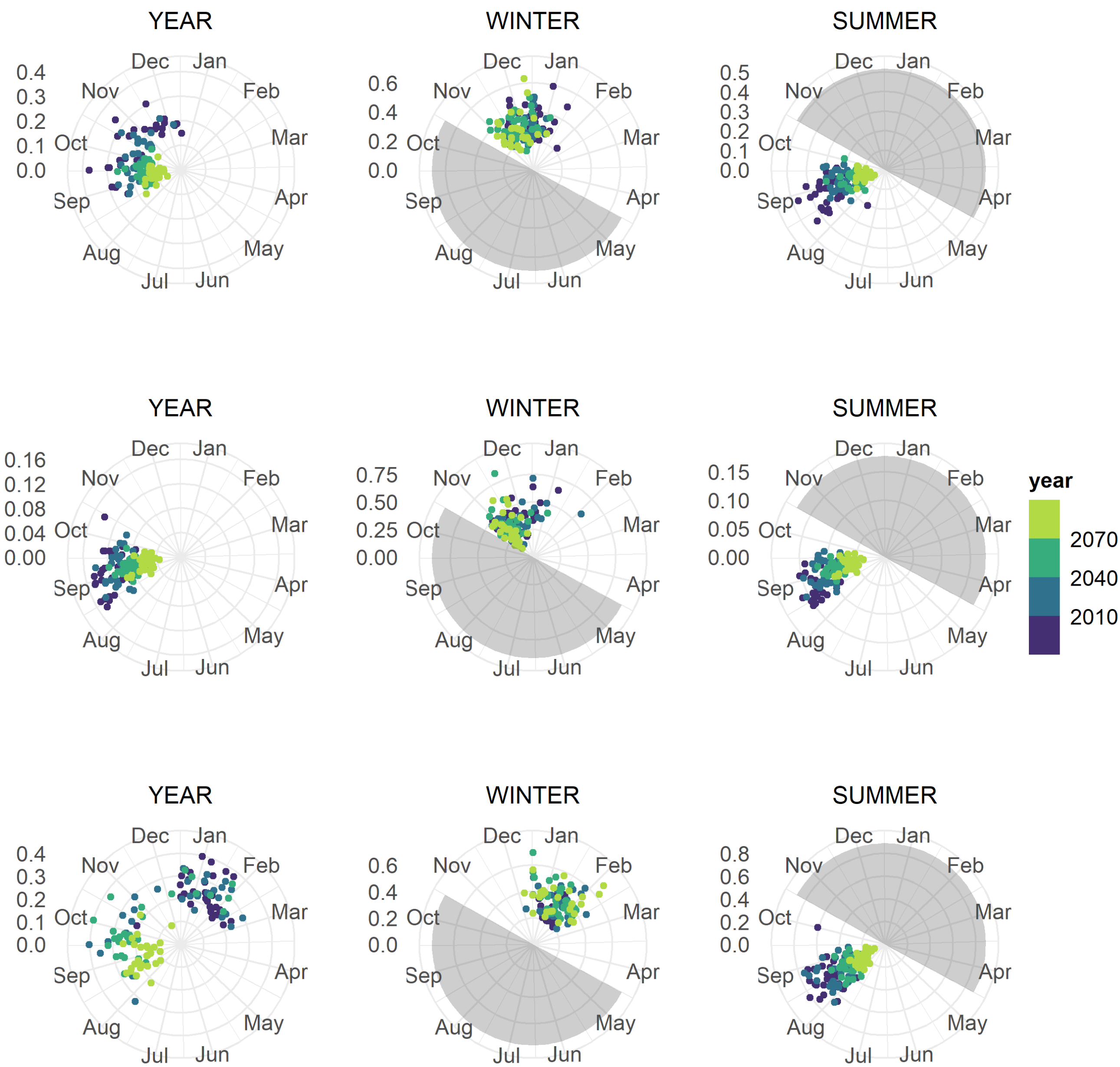

Figure 5: Multi-model median of intensity and seasonal occurrence of low flows and seasonal lowest flows in low lying catchments: Emme (top row), Venoge (middle row), and Verzasca (bottom row).

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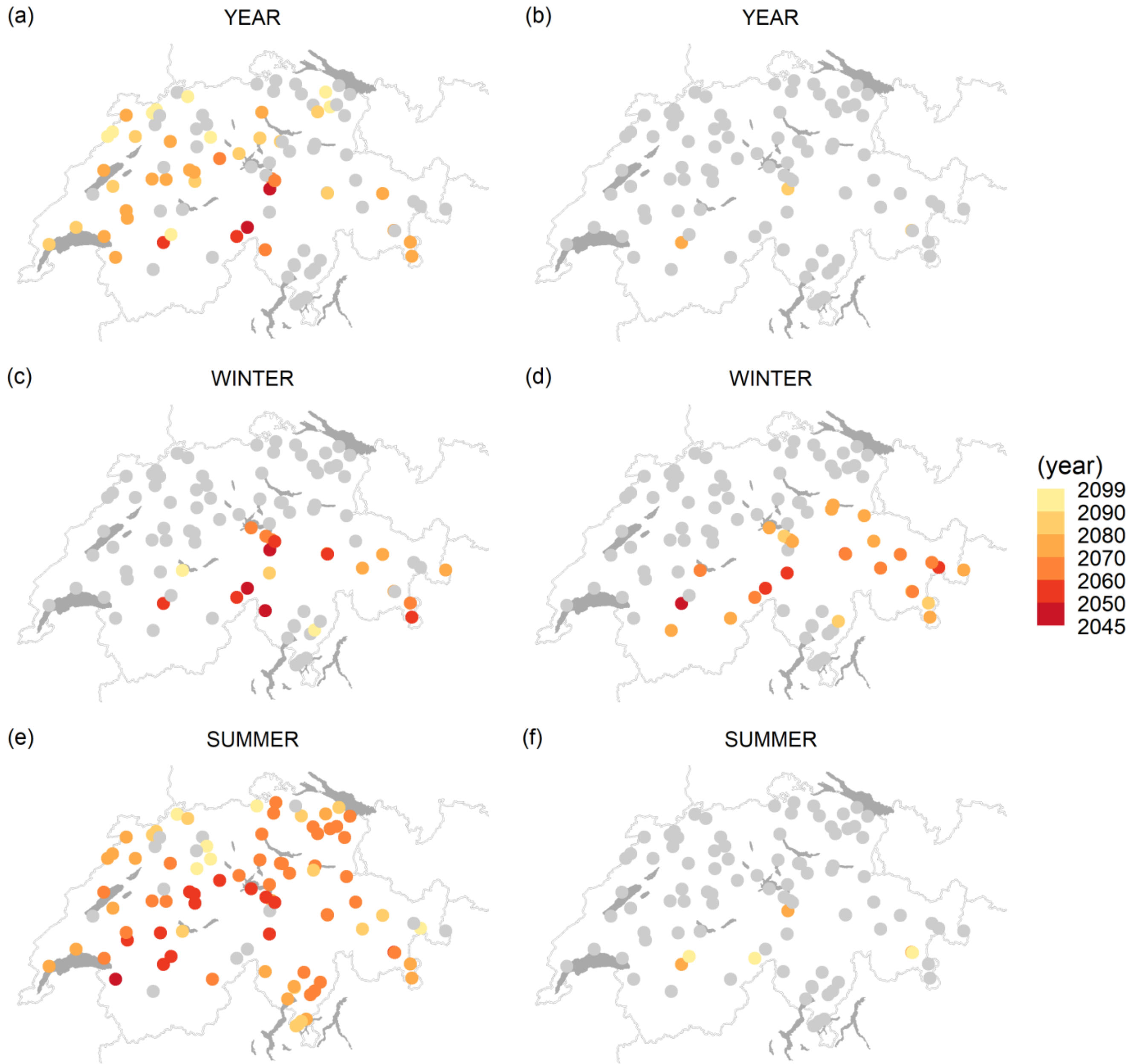

540 **Figure 6: Time of emergence of moderate low flows (left panels) and moderate high flows (right panels) when at least 66% of the models agree on significant changes in the distribution of moderate low and high flows, respectively.**

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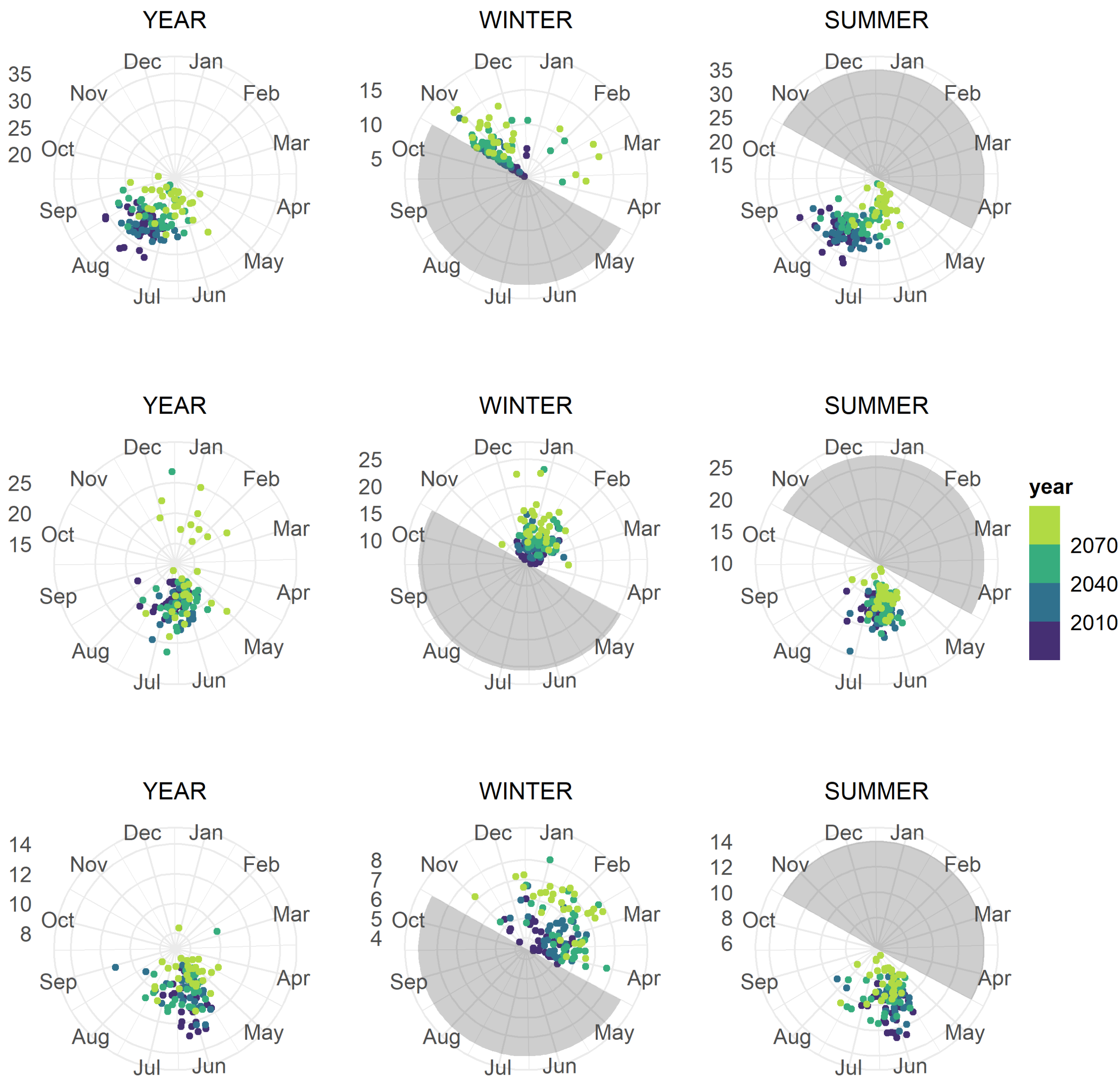

Figure 7: Multi-model median of intensity and seasonal occurrence of high flows and seasonal highest flows in Alpine catchments: Rosegbach (top row), Kander (middle row), and Plessur (bottom row).

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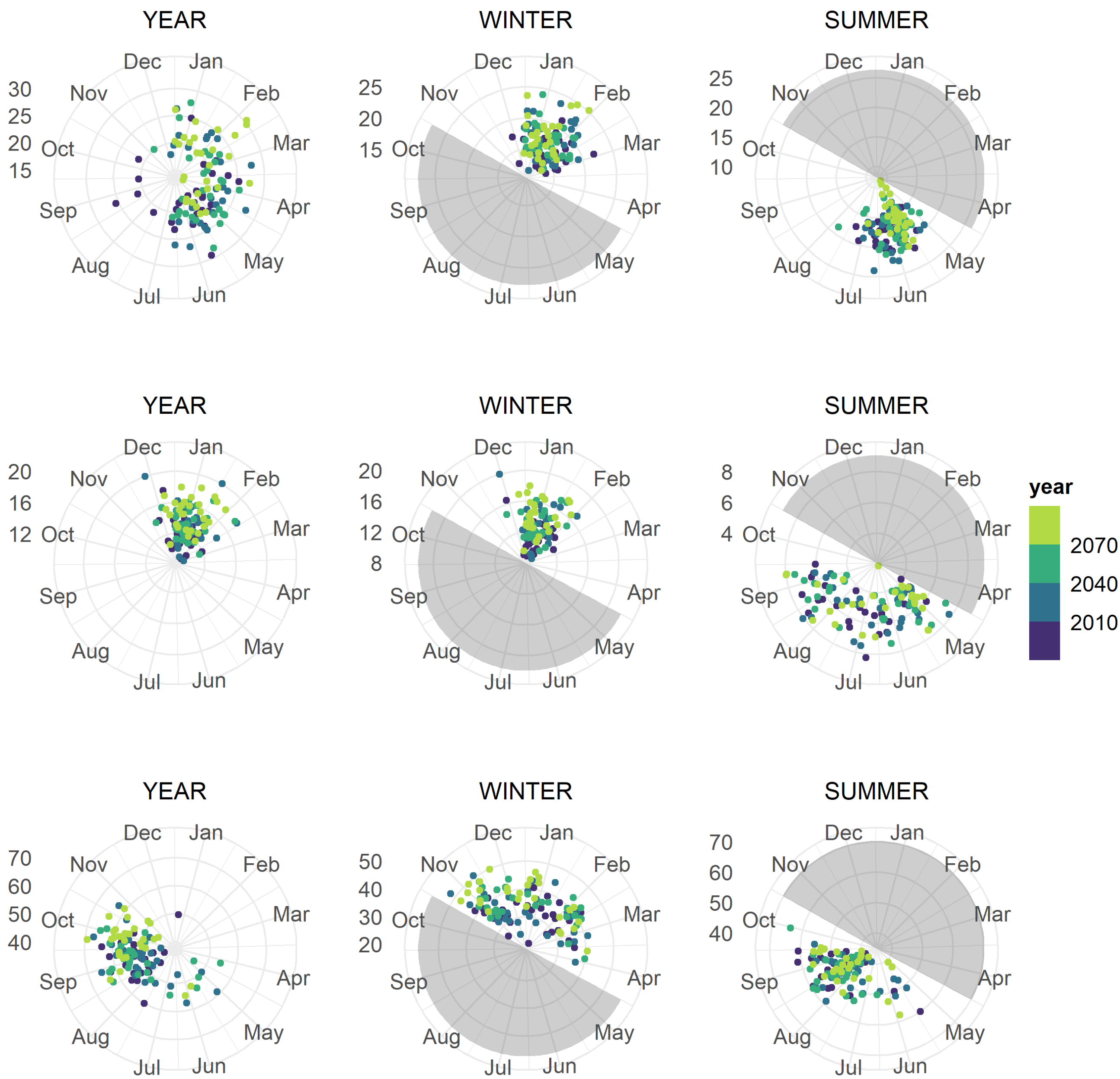

550 **Figure 8: Multi-model median of intensity and seasonal occurrence of high flows and seasonal highest flows in low lying catchments: Emme (top row), Venoge (middle row), and Verzasca (bottom row).**

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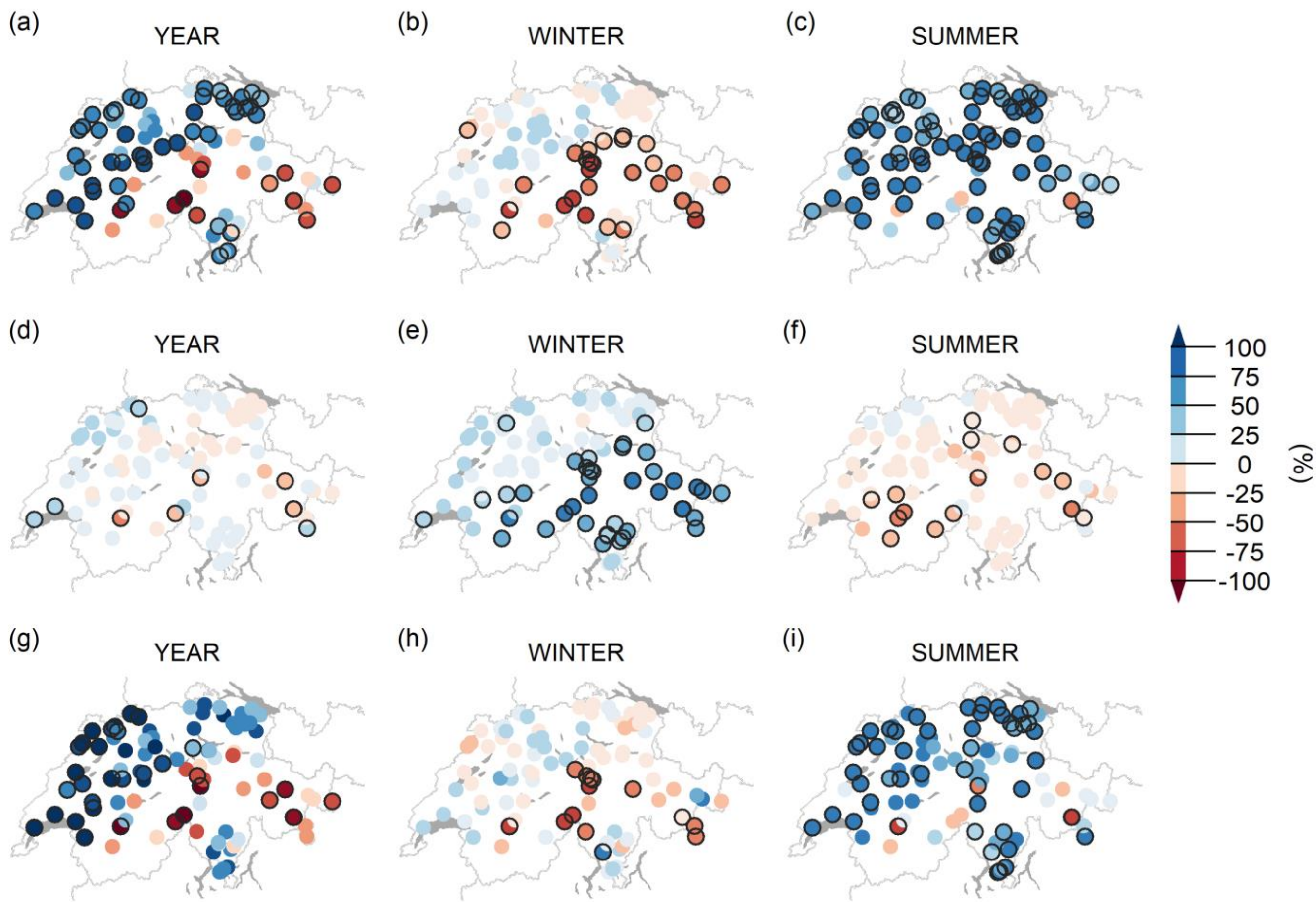

555 **Figre 9: Relative changes in the frequency of occurrences of moderate low flow events (lower than the median of the reference period, top panels), of moderate high flow events (higher than the median of the reference period, middle panels), and co-occurrence of low and high flow events (bottom panels) by end of the century. Black circles indicate changes with at least 90% of the models agreeing on the direction of change.**