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Seasonality and magnitude of floods in Switzerland under future climate change

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Abstract:

The flood seasonality of catchments in Switzerland is likely to change under climate change because of anticipated alterations of precipitation as well as snow accumulation and melt. Information on this change is crucial for flood protection policies, for example, or regional flood frequency analysis. We analysed projected changes in mean annual and maximum floods of a 22-year period for 189 catchments in Switzerland and two scenario periods in the 21st century based on an ensemble of climate scenarios. The flood seasonality was analysed with directional statistics that allow assessing both changes in the mean date a flood occurs as well as changes in the strength of the seasonality. We found that the simulated change in flood seasonality is a function of the change in flow regime type. If snow accumulation and melt is important in a catchment during the control period, then the anticipated change in flood seasonality is most pronounced. Decreasing summer precipitation in the scenarios additionally affects the flood seasonality (mean date of flood occurrence) and leads to a decreasing strength of seasonality, that is a higher temporal variability in most cases. The magnitudes of mean annual floods and more clearly of maximum floods (in a 22-year period) are expected to increase in the future because of changes in flood-generating processes and scaled extreme precipitation. Southern alpine catchments show a different signal, though: the simulated mean annual floods decrease in the far future, that is at the end of the 21st century.

KEY WORDS flood seasonality; flood magnitudes; climate change impact; Switzerland; ENSEMBLES

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INTRODUCTION

There is a general perception that the magnitude and frequency of floods might increase with climate change. Modelling studies suggest that higher temperatures provoke higher water holding capacities of the atmosphere and therefore a higher probability of extreme precipitation events (Boroneant *et al*., 2006; Beniston, 2012). The anticipated increase in heavy precipitation results in an increased flood risk, consequently (Booij, 2005; Tu *et al*., 2005; Cunderlik and Simonovic, 2007; Pall *et al*., 2011). Results from Schmocker-Fackel and Naef (2010a) suggest that observed '[...] changes in atmospheric circulation might be responsible for the changes in flood frequency [...]' in Switzerland since 1850. The authors also state, however, that the increasing trends they observed might be biased through an accumulation of large floods at the end of the 20th century. Moreover, another study by Schmocker-Fackel and Naef (2010b) showed that these floods at the end of the 20th century are still in the range of observed floods since 1500. So for Switzerland, there is an indication, but there is no evidence of a relationship between increasing flood frequencies and changes in climate. And a number of recent studies in other regions demonstrate that this relationship cannot be observed for measured discharge records of the 20th century where a substantial change in climate has already occurred (e.g. Hirsch and Ryberg, 2012). This is mostly ascribed to the record length that is most often too short to allow for detection of trends in the time series because extreme events are rare per definition (IPCC, 2012). Additionally, the strong natural variability of hydrological records hinders trend detection (Kundzewicz *et al*., 2012) because the change in a variable could have been also produced randomly by internal variability (Kundzewicz and Cramer, 2012).

Although changes in climate extremes are likely (IPCC, 2012), their projections are highly uncertain too (CH2011, 2011). Regarding precipitation, something that certainly changes, though, is the ratio of liquid to solid precipitation (due to increasing temperatures), which substantially alters the nature and processes of floods in a mountainous environment such as Switzerland. The anticipated seasonal shift in precipitation (decrease in summer and increase in winter; CH2011, 2011) is likely

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to alter the runoff behaviour and flood generation, additionally, so that the most obvious change in the distribution of floods will be a seasonal change (Sivapalan *et al.*, 2005; Blöschl *et al.*, 2011). Moreover, flood seasonality (and its change) is assumed to be the key factor to understand the impact of climate change on floods (Blöschl *et al.*, 2011).

The flood seasonality of a catchment can be interpreted as the likelihood of floods to occur during a certain period (Bayliss and Jones, 1993). This information is vitally important for water management, flood protection policy or regional flood frequency analysis. In recent years, seasonality measures have increasingly been used to characterize flood generating processes or classify flood regions. Merz and Blöschl (2003), for example, used directional statistics to analyse flood process types in Austria at the regional scale. Parajka *et al.* (2010) used seasonality measures to study flood generating processes by comparing the seasonal statistics of extreme precipitation and floods across the Alpine–Carpathian range. Piock-Ellena *et al.* (2000) used seasonal analysis for regionalization of floods in Switzerland and Austria. Black and Werritty (1997) applied directional statistics to classify flood seasonality. Pfaundler and Wüthrich (2006) assessed the seasonality of Swiss catchments in general, and for case studies, they tested different time periods in the 20th century for changes in seasonality. Wehren (2010) applied seasonality measures in a climate sensitivity study in a Swiss catchment. To our knowledge so far, no study used the seasonal analysis of floods in climate impact studies driven by state of the art climate scenarios.

We study the effect of climate change on the seasonality of floods in 189 mesoscale catchments in Switzerland that represent the range of different catchment types and hydrological processes (Köplin *et al.*, 2012). Earlier studies demonstrated the clear spatial pattern of flood seasonality in Switzerland during control period conditions, that is at the end of the 20th century (Piock-Ellena *et al.*, 2000; Pfaundler and Wüthrich, 2006). How does this spatial pattern of flood seasonality change as a result of climate change? And can this change be attributed to changes in the flood generating processes?

We will analyse projected changes in flood magnitudes and examine the spatial distribution and variability of these changes to identify general tendencies and possible regional patterns that would indicate changes in the triggering processes. Moreover, we will analyse the simulated change in the type of floods, that is the spatially distributed seasonality of floods in Switzerland during control period conditions and for two scenario periods in the 21st century. For selected and representative case studies, the anticipated change in the causal processes is studied in detail.

DATA AND METHODS

The hydrological model used in this study is the semi-distributed and conceptual, process-oriented model PREVAH (Precipitation-Runoff-EVApotranspiration-Hydrotope based model; Viviroli *et al.*, 2009a). The calibration procedure applied here involves an iterative pairwise calibration of 12 tuneable model parameters (14 for glaciated catchments) that is evaluated with a linear and logarithmic Nash–Sutcliffe efficiency, a volumetric deviation measure as well as different peak flow sensitive scores (see Viviroli, 2007 and Viviroli *et al.*, 2009b for a detailed documentation). This is to assure the good representation of both the water balance and peak flows of a catchment, which was demonstrated in Köplin *et al.* (2010), Viviroli (2007) and Viviroli *et al.* (2009b).

The calibrated parameter sets were transferred to catchments without runoff data and to those with discharge records that are influenced by hydropower production. We did this to assess the hydrological impact of climate change on a set of catchments that represents all different regime types and, therefore, runoff generation processes in Switzerland. Briefly speaking, the regionalization procedure is a combination of three different regionalization approaches and is described in Viviroli (2007) and Viviroli *et al.* (2009c) in detail. The regionalized parameter sets were extensively validated and evaluated for their use in assessing high flow conditions in the study domain (Viviroli, 2007; Viviroli *et al.*, 2009c; Viviroli and Weingartner, 2011; Köplin, 2012). They proved good representation of peak flows as well as hydrological plausibility.

For 189 catchments, model simulations in hourly resolution for the control period from 1984 to 2005 and two scenario periods (2025–2046, 2074–2095) were compiled. The required climate scenario data were provided by the CH2011 initiative (CH2011, 2011). Here, daily scenarios of ten different combinations of global climate models (GCMs) and regional climate models (RCMs) from the ENSEMBLES project (van der Linden and Mitchell, 2009) were used. The ten GCM–RCM model chains are post-processed through an extended delta change method (Bosshard *et al.*, 2011) and are provided at 188 temperature and 565 precipitation stations. Because of the post-processing with the delta change method, the climate scenario data incorporate the wet and dry-day frequency of the observations and represent the changes in the mean annual cycle of precipitation and temperature. Future extreme precipitation is only considered as far as observed extremes are scaled. This is clearly a limitation with respect to the analysis of floods, of course, and we are well aware that we do not study the full possible range of changes in flood magnitudes. Therefore, we do not extrapolate the time series both because of the delta change scenarios and the rather short simulation period of 22 years. The annual distribution of precipitation as well as the proportion of liquid and solid precipitation is altered in the climate scenarios, though. Moreover, evapotranspiration changes in the scenarios because it is calculated with the Penman–Monteith equation and is thereby indirectly influenced through the changed temperature (please see Köplin *et al*., 2013 for details). The changed evapotranspiration and precipitation regimes in turn alter the soil moisture storage and therewith the antecedent soil-moisture conditions or in other words the soil moisture deficit. For those reasons, we assume that we analyse the underlying hydrological change signals in our study, separated from changes in climate extremes.

Necessary scenarios of glacier retreat were provided within the project Climate Change and Hydrology in Switzerland (Volken, 2010; FOEN, 2012), which this study is part of. They are based on an increase of the equilibrium line altitude and a subsequent adaptation, that is retreat of the ablation zone (Paul *et al*., 2007). The increase in equilibrium line altitude is simulated according to the projected temperature increase of the climate scenarios (Linsbauer *et al*., 2013).

The analysis in this paper is based on annual maximum series (AMS). Frequently, a threshold value of 7 days between two peaks is applied to guarantee independence of two events (Maniak, 2005). The only possible situation where two peaks of an annual series are not independent is around the turn of the year, of course. We analysed the AMS and found that all 189 flood series are independent events. Deciding on the AMS to extract the mean annual flood might, however, lead to sampling of a peak that is not a flood but only the highest measured runoff of a particular year. Another frequently used sampling method, the peaks-over-threshold method (POT), would prevent sampling a discharge value that is no extreme value. For discharge series of >20 years, however, AMS are preferred (Maniak, 2005) because they describe the high flow behaviour of a catchment evenly over time. Because the simulated discharge series in our study cover 22 years, we decided on the AMS to sample peak runoff. It has to be stated, though, that the simulated peaks represent the maximal hourly mean of a flood (as a result of the temporal modelling resolution) and not the highest instantaneous peak flow.

Three different high flow characteristics are derived from each AMS: the mean annual flood (HQ_{MEAN}), that is the mean value of all 22 peaks, the maximum flood of the 22 year period (HQ_{MAX}) and the coefficient of variation (*CV*). This latter dimensionless ratio of standard deviation and HQ_{MEAN} is used to compare the variation of peak flows in different catchments, particularly in catchments with varying size. To compare the discharge of differently sized catchments in another way, we compared their specific discharge rates (Hq_{MEAN}, Hq_{MAX}), defined as HQ_{MEAN} or HQ_{MAX} divided by catchment area. We evaluated the plausibility of simulated Hq_{MEAN} and Hq_{MAX} by comparing the simulated control period values to 54 catchments where natural discharge records in hourly resolution were available for the period 1984–2005. Those catchments cover roughly the same range of catchments sizes such as the study catchments.

Besides these measures that describe the quantitative aspects of floods, we studied the flood seasonality and its change. We calculated the seasonality following Bayliss and Jones (1993) and Burn (1997): each annual peak i of the AMS can be described with its day of occurrence given as Julian date and converted to an angular value in radians as

$$\theta_i = (\text{Julian date})_i \left(\frac{2\pi}{365}\right), \tag{1}$$

with Julian date 1 being January 1. The x and y-coordinates of the mean date of flood (MDF) can be calculated as

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} \cos\theta_i \tag{2a}$$

and

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} \sin\theta_i. \tag{2b}$$

The mean date of the floods as an angular value, $\bar{\theta}$, is calculated as

$$\bar{\theta} = \tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) \quad \text{for } \bar{x} \geq 0 \tag{3}$$

and

$$\bar{\theta} = \tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) + \pi \quad \text{for } \bar{x} < 0. \tag{4}$$

The angular value of the mean date of flood can be converted back to a Julian date *MDF* as

$$MDF = \bar{\theta}\frac{365}{2\pi} \tag{5}$$

and the corresponding length of the seasonality vector r is calculated as

$$r = \sqrt{\bar{x}^2 + \bar{y}^2} \tag{6}$$

with a value of 1 meaning all floods occur on the same date. We define r-values >0.6 as a strong or clear seasonality, which means that there is a distinct season where most annual maxima occur. Smaller r-values indicate long or diverse flood seasons and thereby a weak seasonality, that is no concentration of annual maxima in a certain season. However, please notice that a small *r* does not neccessarily imply equally distributed floods throughout a year. This value could actually mask a bimodal or multimodal distribution of floods. An extreme example would be half of the floods occur on January 1, half of the floods on July 1, then the resulting *r* would have a length of zero, but there is actually a strong bimodal flood seasonality. We analyse the changes in seasonality together with the causing processes, therefore, which will prevent misinterpretation of short seasonality vectors.

RESULTS AND DISCUSSION

We analysed the simulated control period Hq_{MEAN} and Hq_{MAX} first, to test the simulations for their physical plausibility (Figure 1). We plotted the simulated values of the 189 study catchments together with observed values of 54 similarly sized catchments: The simulated values for the control period are within the range of observed Hq_{MEAN} and Hq_{MAX}. The specific discharges of catchments with an area less than 40 km^2 tend to be underestimated by the hydrological model, though. This effect was already observed in a study by Viviroli and Weingartner (2011), who assessed the use of the applied regionalization procedure for flood estimation in small to mesoscale catchments in Switzerland. They found that the model's capability to adequately reproduce very fast runoff components that are important in small catchments is limited. Because only four catchments out of 189 in our study have an area of 40 km^2 or less, we assume that the model performance to simulate flood discharge is appropriate for our purpose. We also plotted the envelopes of maximum observed instantaneous peak flows (Weingartner, 1999, Figure 1) to compare our results with these statistical relationships between catchment area and peak flow rate: if the simulated values are on or below the envelope, then the simulation is within the range of the observation. The two large catchments that lie above the northern envelope are no outliers. Those are two catchments in the Ticino basin situated in the southern alpine region of Switzerland, where a different relationship between catchment size and Hq_{MAX} is valid ('southern envelope', Figure 1).

We calculated the specific discharges for single GCM–RCMs (Figure 2) to examine possible tendencies of the driving GCM to bias the projected mean (see Table I for an overview on the ten GCM–RCMs). For Hq_{MEAN}, no pattern regarding the driving GCM is observed; the spread due to single GCM–RCMs is negligible. For Hq_{MAX}, the highest values in the scenario result more often from model chains driven by the HadCM-GCM (red), but this pattern is not consistent for all catchments in the far future (bottom-right panel in Figure 2). The climate model chains driven by this GCM project a strong increase in temperature throughout the year, that is both in winter and summer (CH2011, 2011). This might lead to higher proportions of liquid precipitation in winter, which, together with generally increased winter precipitation amounts, subsequently leads to increases in the Hq_{MAX} values. A general pattern observed for Hq_{MAX} is the large spread in projections due to single GCM-RCMs. In most catchments, a range from slight decrease to strong increases of Hq_{MAX} is projected. For Hq_{MAX} >1.5 m^3/s km^2 in the control period (*x*-axis), the GCM-RCMs reveal a clear pattern for the far future (bottom-right panel). The ARPEGE-GCMs and BCM-GCMs (yellow and green) project slightly decreasing Hq_{MAX} values, whereas the ECHAM-GCMs (blue) produce slightly increasing values, and the HadCMs (red) result in the strongest increase in Hq_{MAX}. This large spread from decrease to strong increase can be interpreted as a larger uncertainty in the projections for the far future period.

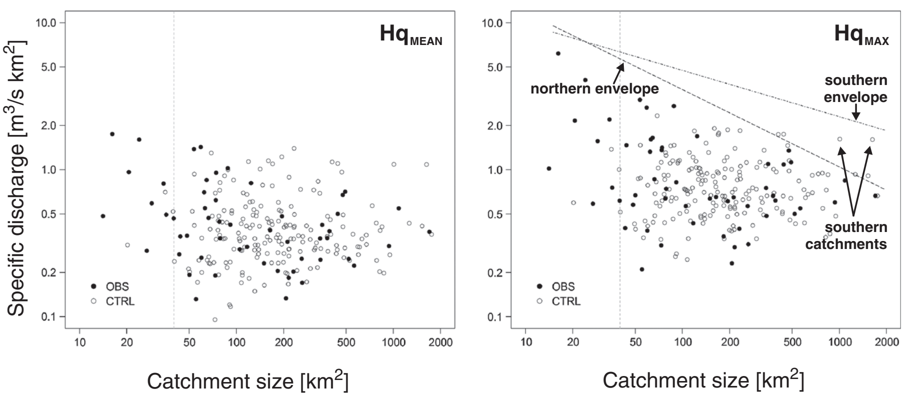

Figure 1. Hourly means of specific discharge (left, HqMEAN; right, HqMAX) for 54 observed natural discharge records (OBS) and simulated control period discharge (CTRL). The dashed vertical lines indicate the catchment size below which the hydrological model performance in simulating high runoff is limited (<40 km^2). The envelopes of maximum observed instantaneous peaks for the northern and the southern alpine area are indicated for comparison (Weingartner, 1999)

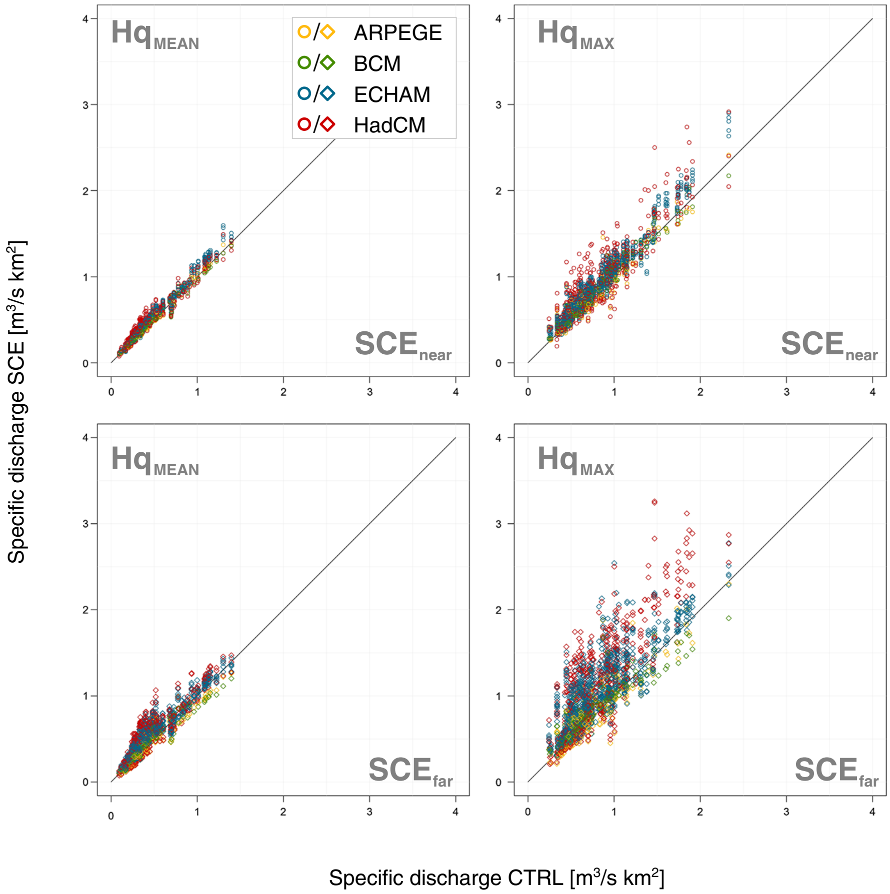

Figure 2. Global climate model spread of simulated HqMEAN (left) and HqMAX (right) for the near (top) and the far future (bottom). The one-to-one line is indicated for comparison

Table I. Applied climate model chains from the ENSEMBLES project, post-processed and provided by the CH2011 initiative (CH2011, 2011)

Institution	Global climate models	Regional climate models
CNRM	ARPEGE	ALADIN
DMI	ECHAM5	HIRHAM
ETHZ	HadCM3Q0	CLM
HC	HadCM3Q0	HadRM3Q0
ICTP	ECHAM5	REGCM
KNMI	ECHAM5	RACMO
MPI	ECHAM5	REMO
SMHI	BCM	RCA
SMHI	ECHAM5	RCA
SMHI	HadCM3Q3	RCA

To visualize the projected change in specific discharge more clearly, we displayed the respective specific Hq values of all catchments together in boxplots and independent from catchment area (Figure 3). The spread in projected specific discharge is larger for the far future period. The notches at the boxes can be used to compare the medians of two boxes; if the notches do not overlap (indicated for Hq_{MAX}, Figure 3), the medians of the two samples differ significantly with an estimated 95% confidence interval (Chambers *et al.*, 1983). All medians in Figure 3 differ significantly, particularly those of Hq_{MAX}. Technically speaking, however, this assumption only holds for roughly equal sample sizes, which is not true for comparisons between the control and the scenario periods (the scenario samples have ten times the size of the control sample because of the ten GCM-RCMs). Still, the obvious differences between the medians indicate an increase of Hq_{MEAN} and more pronounced of Hq_{MAX} because of scaled extreme precipitation. Additionally, a change in the triggering processes might be observed here, for example an increase of rain-on-snow floods. This assumption will be addressed later in this section.

The spatial patterns of changes in absolute HQ_{MEAN} and *CV*, given as ratios of scenario ensemble mean to control period (Figure 4), explain the observed increase in specific Hq_{MEAN}. The absolute HQ_{MEAN} increases uniformly but rather slightly (between 5 and 24%) in the near future period. This is a robust signal because in most catchments, 9–10 (out of 10) GCM-RCMs agree in the sign of the change, with the exception of catchments in the central south (Ticino catchment) and the northeast (Thur catchment). In the far future, a strong increase (25–49% and higher in some catchments) in HQ_{MEAN} is projected for the high alpine area and the western Prealps. Again, 9–10 GCM-RCMs agree in the sign of the change. A possible reason might be the increased proportion of liquid precipitation in these areas in the future. For the Ticino and the upstream part of the Thur catchment, no change in the far future HQ_{MEAN} is observed relative to the control period. The coefficient of variation as a measure of flood variability shows no obvious spatial pattern for the near future period; the change ranges from −25% to an increase of >50%. The picture is somewhat clearer in the far future period. Catchments situated in the Jura mountain ranges (northwestern Switzerland) show decreasing *CV*s. This might be ascribed to an increasing seasonality in those catchments, which will be explained in the following paragraph. Most catchments at higher elevations show robust and sharp gradients from control to scenario in the far future.

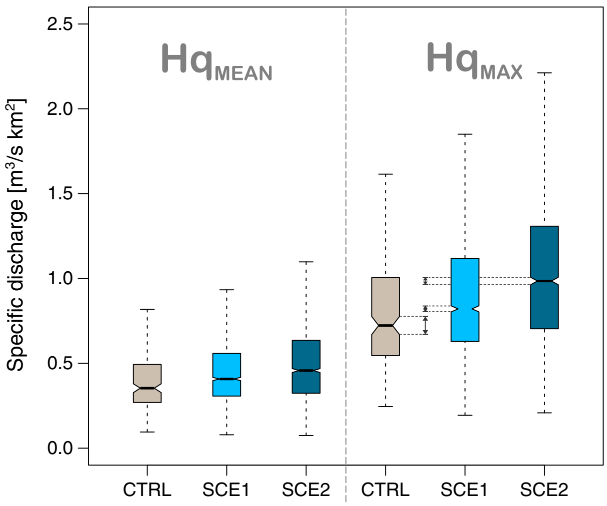

Figure 3. Boxplots of projected specific discharges (left, HqMEAN; right, HqMAX) of all 189 catchments for the control period (CTRL), the near future (SCE1) and far future period (SCE2)

In the following, the results for the projected changes in flood seasonality are described. The flood seasonality of the study catchments, depicted by seasonality vectors in Figure 5, shows a distinct spatial pattern for the control as well as the scenario periods. We subdivided the seasonality vector maps into five seasonality regions that correspond to the dominant hydrological regimes of the control period (Weingartner and Aschwanden, 1992) and that are summarized in the following. Interestingly, the spatial structure and grouping of the seasonality vectors does not change from the control to either one of the scenario periods, except for the pluvial zone that would actually stretch farther south in the western part in the far future (lower-right panel in Figure 5). The reason therefore is that flood seasonality is directly related to the hydrological regime (Pfaundler and Wüthrich, 2006). Changes in the regime due to climate change are translated to changes in flood seasonality, which are then similar for the different regime types.

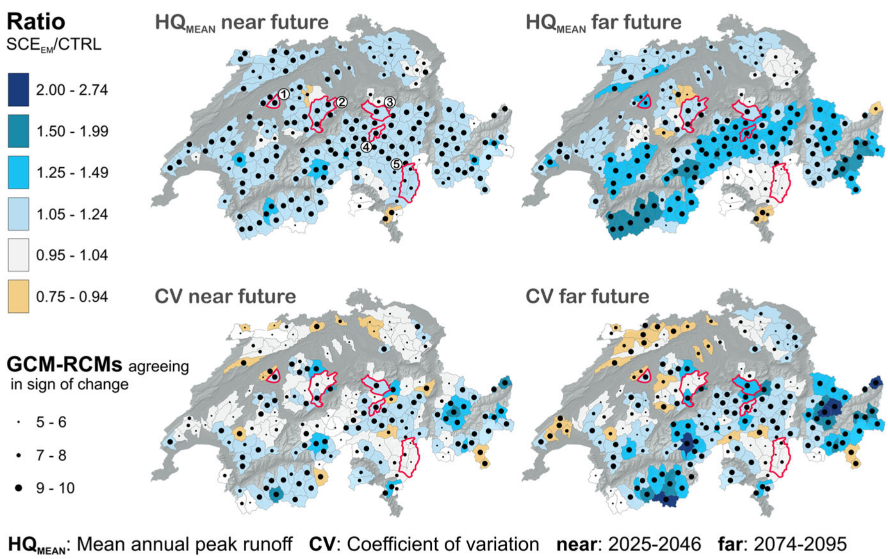

Figure 4. Projected change in HQ_{MEAN} (top row) and CV (bottom row) for the near (left) and far future period (right). The relative change is given as the ratio of scenario ensemble mean (SCE_{EM}) over control period (CTRL). Values >1 indicate an increase (blue colours) and values <1 a decrease (beige). No clear signal is observed for the class from 0.95–1.04. The number of GCM-RCMs that agree in the sign of change indicates the robustness of the change signal. Five catchments are highlighted in red, for which detailed results are presented in Figure 6

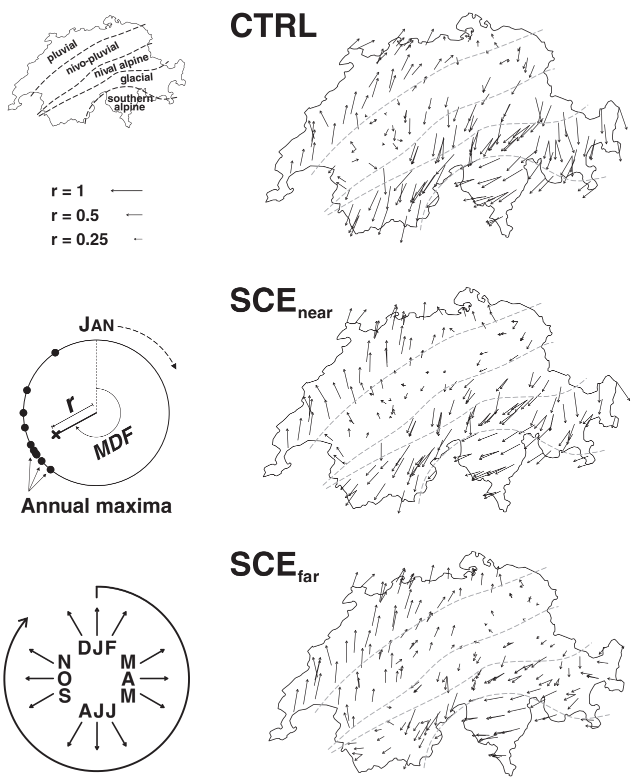

Figure 5. Seasonality vectors for control (CTRL, top-right), near future (SCE_{near}, middle-right) and far future period (SCE_{far}, bottom-right). A vector's origin is at the outlet of a catchment. In the top-left corner, a generalized visualization of the five main regime regions (Weingartner and Aschwanden, 1992) during the control period is depicted. The regime regions are indicated in the seasonality vector maps on the right side, too, to ease orientation and comparison. Below the regime overview on the left side, the scale for r is given. A value of 1 means all floods occur on the same date, whereas small values indicate high seasonal variability. Below the scale, the schematic visualizes how to build and read a seasonality vector. The vector points to the average date of annual maxima (×, centroid of all maxima) given in radians and starting at 0 rad in January moving clockwise. In the bottom-left corner, the direction of seasonality vectors are summarized and grouped to the four seasons

Pluvial catchments in the northwestern part of Switzerland have a pronounced winter to early spring flood seasonality, which marginally changes to earlier winter in the near and far future period and this with a stronger seasonality. Nivo-pluvial catchments, which are characterized by a mixture of snowmelt and rain-fed runoff processes, have a less marked seasonality in the control period with a tendency towards summer floods. Their weak seasonality decreases further in the near future period and increases in the far future. In that scenario period, however, the catchments exhibit a tendency towards winter floods, which indicates a marked change in flood-generating processes for nivo-pluvial catchments. The regime of nival alpine catchments is strongly determined through snow-melt processes and those catchments therefore show a clearer seasonality in the control period. This clear seasonality decreases successively from control to the near and far future period and changes from mid over late summer to early autumn floods in the far future. For glaciated catchments, the floods in the control period are in late summer, and seasonality is strong in general, although it successively decreases here, too. The timing of floods does not change significantly, though. The last regime type, which is typical for the southern part of Switzerland, is characterized by early autumn floods with a very clear seasonality. In this region, the seasonality hardly changes in the scenario periods, neither with respect to strength nor timing.

The results of the seasonal analysis for control period conditions reflect the results of Diezig and Kan (2010) for approximately 70 catchments with discharge measurements in the period 1971–2007. The subdivision into five main regions are in good agreement with the results from Piock-Ellena *et al.* (2000), who analysed an extensive set of 793 discharge records in Switzerland and Austria and sought homogenous regions for the regionalisation of floods. Their classification of the Swiss part of the study region matches with our subdivision of catchments into the main regime types indicated in Figure 5. The general pattern was also described by Pfaundler and Wüthrich (2006). The hydrological regime is basically a function of elevation. Therefore, our differentiation of flood seasonality and seasonality change is determined by elevation, to a large part. Parajka *et al.* (2009) came to the same conclusion, namely that '[...] altitude is one of the key factors that control the temporal stability and spatial variability of hydrological regime and flood seasonality [...]' in a mountainous environment. Decreasing seasonality was also observed in a climate sensitivity study in the northern alpine Kander catchment (Wehren, 2010), which has a glaciation of 5.6% in the control period. There, a clearly decreasing seasonality was simulated for increasing temperatures and more or less independently from the assumed precipitation changes, that is for both, increasing or decreasing precipitation. This sensitivity study suggests that the change in the strength of the seasonality in catchments where melt processes are important depends strongly on the temperature signal.

These results in changes of seasonality mirror a change in regime type, as mentioned earlier. Recent studies on hydrological impacts of climate change in Switzerland demonstrated a shift of the regime types to higher elevations in the future, e.g. snow-fed regime types will be found at higher elevations in the future than today (e.g. Horton *et al.*, 2006; Schädler and Weingartner, 2010; FOEN, 2012; Köplin *et al.*, 2012). The shift of the hydrological regime implies a change in the dominant runoff generating processes, i.e. an increasing proportion of liquid precipitation leads to increased direct runoff, for example. The same applies to shifts in flood seasonality: the causing processes are altered through climate change which will be explained in the following with the example of five case study catchments that represent the range of regime types.

Although the change in flood seasonality and its causal processes is specific for every catchment, certain relationships are observed for greater regions as stated before. Each of the case study catchments (Figure 6) represents one regime type with its associated changes in flood seasonality. The complex Figure 6 will be described row

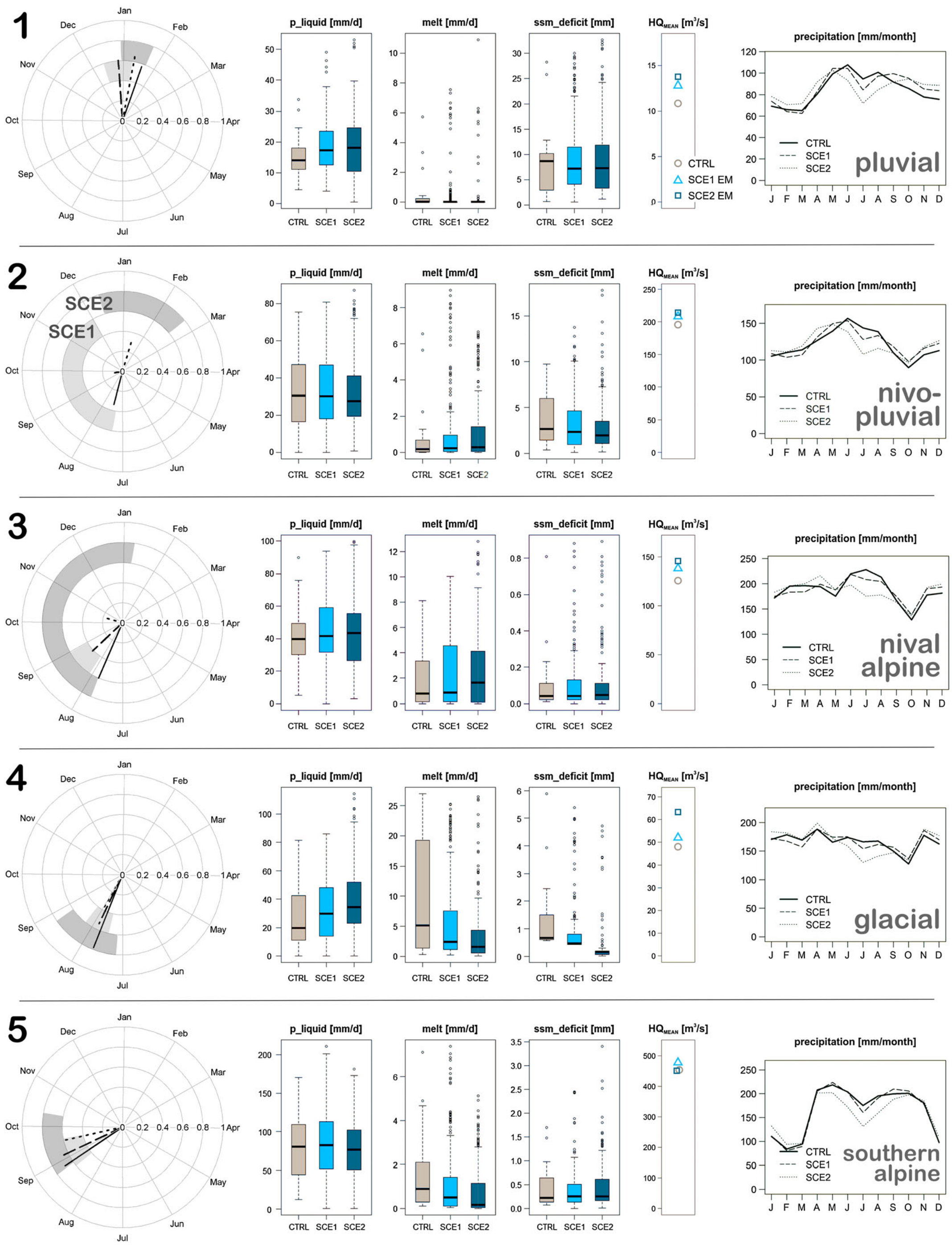

Figure 6. Detailed analysis of five case study catchments; for their spatial locations see Figure 4, the names of the main rivers are given in Table II. On the left side of each row, the seasonality vectors for the control (solid line), the near future (dashed line) and the far future period (dotted line) are shown on polar plots. The seasonality vectors of the scenarios represent the ensemble mean. The grey-shaded sectors depict the range of ±1 standard deviation around the ensemble mean for SCE1 and SCE2 (see catchment 2 for the legend). The boxplots in the middle part of each row show event-based proportions of the input variables liquid precipitation (p_liquid) and snow and ice melt (accumulated to total melt), as well as event-based soil moisture deficits (ssm_deficit). Please note the different scales of the panels. To the right of the boxplots, the projected change in HQ_{MEAN} is shown for control (CTRL) and scenario ensemble mean values (SCE1 EM, SCE2 EM). At the right side of each row, the annual cycle of monthly precipitation for the control and the scenario ensemble means are visualized

by row in the following. For the pluvial catchment 1 (see Table II for additional information), the event-based amount of precipitation increases from the control to the scenario periods. *Event-based* is defined as the daily liquid precipitation, daily melt amounts or mean daily soil-moisture deficit, respectively, that were simulated on the dates the annual floods occurred. We analysed the three-day and five-day sums, too (not shown here) and found that three-day sums explain the flood discharge better in some larger catchments. For the presented mesoscale case study catchments, the one-day values were more meaningful, though.

The increase in event-based liquid precipitation in catchment 1 causes an increase of the winter seasonality; melt processes are only involved in some floods (outliers outside the whiskers) in this catchment. The median of soil moisture deficit is lower in the scenario periods, which indicates wetter conditions in the future before a flood occurs. The annual cycles of precipitation show increases in autumn and winter precipitation, which is why the winter flood season is intensified (larger *r*) and the HQ_{MEAN} values increase. Compared with the other catchments, these absolute HQ_{MEAN} values are very low in this small catchment (catchment area given in Table II).

The nivo-pluvial catchment 2 shows no clear change in the event-based inputs for the near future period. Snow melt has an influence on events, here, but on a rather low level. The rain-fed summer floods in the control period are substituted by rain-fed winter floods in the far future that can be derived from the polar plot on the left side but also from the annual cycle of precipitation to the right: winter precipitation in the far future is higher than the decreased summer precipitation in this period. This change in the season might be a reason for the lower soil moisture deficit during an event, because the soil moisture cannot be significantly depleted through evaporation in winter. The variation in flood season due to single GCM–RCMs is high, however, depicted by the high standard deviation for both scenario periods. The projected increase in HQ_{MEAN} is therefore not a very strong signal.

The range of ±1 standard deviation in catchment 3, the nival alpine example, is the largest of all catchments, indicating a rather unstable state of the hydrological regime and the associated dominant processes at the end of the 21st century. The projected precipitation regime is more balanced in the future, which is one reason for the unspecific seasonality in that period. Liquid precipitation increases in the far future period as well as event-based melt rates. This can be interpreted as an increase of rain-on-snow flood events, which should not be confused, however, with winter seasonality. It is more a diversification of flood types, which is also indicated by the high standard deviation range.

Table II. Summary of catchment properties and simulated changes in seasonality for the five case study catchments (Figure 6). A shift of the season in the scenario period to an earlier (←) or later date (→) is only indicated if the shift is more than a month. The upward and downward arrows (↑, ↓) symbolize an increase or decrease in *r*, that is a change in the strength of the seasonality. The change of HQ_{MEAN} is summarized by upward and downward arrows, too

No.	Name	Regime	Area [km²]	Mean altitude [masl]	Month CTRL	*r* for CTRL	Seasonal change SCE1	Seasonal change SCE2	HQ_{MEAN} SCE1	HQ_{MEAN} SCE2
1	Urtenen	pluvial	90	550	Jan	0.6	↑	↑	↑	↑
2	Kleine Emme	nivo-pluvial	480	1060	Jul	0.3	→↓	→↓	↑	↑
3	Muota	nival alpine	220	1600	Jul	0.6	→↓	→↓	↑	↑
4	Chaerstelenbach	glacial	120	2190	Jul	0.8	↓	↓	↑	↑
5	Moesa	southern alpine	470	1660	Aug	0.7	↓	↓	↑	↓

The glacial catchment 4 shows increases in event-based liquid precipitation, whereas the melt component clearly decreases. The precipitation regime does not change significantly except for a clear decrease of the far future summer precipitation. The formerly pronounced summer seasonality decreases in the future, therefore. HQ_{MEAN}, however, increases clearly, which is explained by higher event-based precipitation amounts of the diversified floods.

The last case study, the southern alpine catchment 5, first shows a slight increase in event-based precipitation in the near future which then decreases below the control period level in the far future. This can be ascribed to the small increase of autumn precipitation in the near future and a subsequent clear decrease of spring to autumn precipitation in the far future. Because the catchments in the southern alpine region are characterized by a strong seasonality of late summer to autumn floods, this case study is the only one where a decrease of HQ_{MEAN} is projected for the far future. In the near future, however, HQ_{MEAN} increases. The results for all five case studies are summarized in Table II.

CONCLUSIONS AND OUTLOOK

We presented an analysis of projected changes in the spatial and seasonal distribution of floods in Switzerland. An extensive set of 189 study catchments that reflect the different hydrological regime types of a mountainous environment was calibrated and regionalized with emphasis on high flow behaviour and run for the control (1984–2005) and two scenario periods (2025–2046, 2074–2095). The whole set of study catchments was subdivided into five regions representing the main regime types pluvial, nivo-pluvial, nival alpine, glacial and southern alpine. Per region, one case study catchment was analysed in detail.

The simulated specific Hq_{MEAN} and Hq_{MAX} discharge of the study catchments increases substantially from the control to both scenario periods, being more pronounced for the far future period. Considering that only changes in the mean annual cycles of temperature and precipitation are assessed and not changes in the frequency or intensity (due to the delta change approach), this increase in Hq_{MEAN} and Hq_{MAX} might seem surprising at first. The picture gets clearer by integrating a spatial component into the analysis and assessing simulated mean annual floods (HQ_{MEAN}); the clear increase in HQ_{MEAN} in the far future is mostly observed for the alpine catchments that experience a strong shift from previously snow-melt dominated runoff processes to a more variable snow and rain-fed regime type. The spatially distributed analysis of flood seasonality confirms this observation. To summarize the results for the anticipated change in flood seasonality (see also Table II), the seasonality of pluvial catchments was strong in the control and gets stronger in the future because the dominant flood generating process – winter liquid precipitation – will be more pronounced in the scenario. Snow-fed and rain-fed (nivo-pluvial) catchments had a weak seasonality in the control that gets stronger in the scenario because of a shift to a solely pluvial regime. Therefore, the flood season of those catchments is projected to change from summer to winter floods. Nival alpine catchments had a clear seasonality in the control that gets weaker as they change to both snow-fed and rain-fed catchments. They seem to be in an unstable state in the far future period, indicated by the highest standard deviation of all catchments. The summer flood season of glacial catchments is not changed but the seasonality gets weaker because the summer precipitation – the dominant process during the control period – decreases in the scenario. Southern alpine catchments do not change markedly with respect to the seasonality, but their HQ_{MEAN} slightly decreases as a result of simulated decreasing event-based precipitation amounts.

Our modelling results for flood seasonality in the control period are in line with other studies in this study domain (Piock-Ellena *et al.*, 2000; Pfaundler and Wüthrich, 2006; Diezig and Kan, 2010). The analysis was based on AMS as the only method to extract mean annual floods from the simulated records. Some studies (e.g. Cunderlik *et al.*, 2004) suggest, however, a POT series might depict a clearer seasonality than the AMS. Although these findings are rather valid for shorter lengths of the discharge records, there might be an effect of the sampling method. Therefore, a possible extension of the analysis in this study would be to sample the mean annual flood record with the POT, too, and compare the resulting seasonality plots with the ones based on AMS. Little differences between the seasonality resulting from the two sampling methods would substantiate the previous conclusions because the flood seasonality would be captured similarly by different sampling methods.

Weingartner *et al.* (2003) defined a threshold elevation of 2000 masl above which flood risk is reduced because of short-term storage of precipitation as snow cover. Wehren *et al.* (2010) defined this threshold even a bit lower at 1800 masl. Our results suggest that the upper limit of the vulnerable zone that starts above 1000 masl (Weingartner *et al.*, 2003; Wehren *et al.*, 2010) might rise substantially in the near and particularly in the far future, increasing the potential for more frequent, that is less seasonal stationary floods in the concerned areas.

It should be stated, again, that we only studied the underlying or basic changes in high flow conditions because of the delta change scenarios that incorporate the precipitation frequency and intensity of the observations.

Our results showed, however, that changes in the considered variables are already substantial. This can be attributed to the strong effect of temperature on the projected floods because increasing temperature alters the ratio of liquid to solid precipitation and thereby the snow line altitude (Blöschl and Montanari, 2010). This is why changes in the seasonality of catchments that are associated with changes in snow line are considered clear signals (Blöschl *et al*., 2011). The next step would be to additionally assess the impact of frequency and intensity changes through different post-processing methods of the climate scenario data, for example. This would allow estimating the relative contribution of both the changes in the mean annual cycle of the climate variables and the changes in their distributions.

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