https://doi.org/10.5194/nhess-2021-93
Preprint. Discussion started: 6 April 2021

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A climatology of sub-seasonal temporal clustering of extreme precipitation in Switzerland and its impacts

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Abstract. The successive occurrence of extreme precipitation events on a sub-seasonal time-scale can lead to large precipitation accumulations, a classic trigger of flood events. Here we analyse sub-seasonal clustering in Switzerland, first characterizing the tendency of precipitation extremes to cluster in time for each season separately, and second, linking the occurrence of persistent flood events to sub-seasonal clusters of precipitation extremes. We find a distinct spatio-temporal pattern in temporal clustering behavior of precipitation extremes, with temporal clustering occurring on the northern side of the Alps in winter, and on their southern side in fall. In winter, the magnitude of precipitation extremes is generally lower, and much of the precipitation falls as snow, therefore temporal clusters contribute little to the occurrence of persistent flood events. In fall, however, temporal clusters associated with large precipitation accumulations over the southern Alps are found to be almost systematically followed by floods. In addition, discharge magnitudes decrease more slowly after clustered extremes.

1 Introduction

Switzerland's climate, topography and high population density make floods one of the major natural disasters, accounting for instance for 71% of weather-related insurance claims over the 1973-2011 period (Swiss Re, 2012) and 36% of total damages to buildings between 1995 and 2014 (BAFU, 2016). Apart from high Alpine regions where summer snowmelt accounts for a large part of the flood risk, floods and landslides over much of Switzerland typically follow widespread heavy precipitation (Froidevaux et al., 2015; Froidevaux and Martius, 2016). Large precipitation accumulations may sometimes result from the occurrence of several extreme precipitation events in close succession. In contrast to persistent but moderate wet conditions, such temporal clusters of extreme precipitation events typically involve more than one day with extreme daily precipitation sums. Such days with intense precipitation can lead to flash flooding (Doswell et al., 1996) or mass movement, especially in urban and mountain areas (Guzzetti et al., 2007; Panziera et al., 2016). Temporal clustering of extremes also complicates rescue, clean-up and repair efforts (Raymond et al., 2020). Clusters of extremes also tend to be missing from risk models which often rely on assumptions of independence in the timing of extreme precipitation occurrence (Priestley et al., 2018).

In Switzerland, several major floods in recent history were linked to series of extreme precipitation events (Barton et al., 2016). In 1993, three events that occurred between September 21 and October 15 led to record 10- to 30-day precipitation accumulations in southern Valais and the Ticino region, and caused repeated oveflowing of Lake Maggiore above its 100-

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year return level. Similar conditions around Lake Maggiore were repeated over the course of four weeks in fall 2000, and again in November 2002, each time bringing the lake above its critical flooding level. The extreme August 2005 floods in central Switzerland were likewise connected to a series of heavy rainfall events in the second half of the month (BAFU and WSL, 2008). Recent other examples of clusters of precipitation extremes leading to major floods include the Pakistan floods of summer 2010 (Martius et al., 2013), the Central Europe floods of summer 2013 (Grams et al., 2014) and the UK floods of winter 2013/2014 (Priestley et al., 2017).

Assessing the temporal dependence in the occurrence of extreme precipitation events at the catchment scale is therefore crucial to accurately quantify flood risks. Such an assessment has not yet been attempted for the whole of Switzerland. Barton et al. (2016) analysed the sub-seasonal serial/temporal clustering of precipitation extremes in Southern Switzerland using a non-parametric approach, Ripley's K function, and found a significant tendency toward clustering during the fall season. They also examined the weather dynamics associated with specific cluster events. At the European scale, Yang and Villarini (2019) quantified the influence of large-scale climate modes on the temporal clustering of extreme precipitation, while Mailier et al. (2006); Vitolo et al. (2009) and Pinto et al. (2013) looked at clustering in winter extratropical storms in the Euro-Atlantic sector, a region where serial cyclone clustering is particularly relevant (Dacre and Pinto, 2020). More recently, Tuel and Martius (2021) attempted a systematic global and seasonal assessment of extreme precipitation temporal clustering at sub-seasonal timescales. Their analysis was however conducted at coarse spatial resolutions relative to the size of Swiss catchments, and focused primarily on clustering signals at large spatial scales.

Additionally, few studies have attempted to evaluate the links between floods and extreme precipitation clusters, and none has conducted such a systematic assessment for Switzerland. The analysis by Barton et al. (2016) focused on selected examples of floods triggered by clusters of extreme precipitation events, as did other studies over Europe (Blackburn et al., 2008; Grams et al., 2014; Huntingford et al., 2014; van Oldenborgh et al., 2015; Priestley et al., 2017; Insua-Costa et al., 2019) or Southwest Asia (Martius et al., 2013). Villarini et al. (2013) considered the temporal clustering of flood events over the American Midwest and its link to large-scale climate patterns, but did not discuss precipitation. Kopp et al. (2021), by contrast, presented a global perspective on the link between sub-seasonal clustering and extremes of cumulative precipitation. In their analysis, however, Switzerland was covered by 3-4 major catchments only, which prevented a discussion of local variability in the results.

Relationships between extreme precipitation and flood occurrence in Switzerland have been more extensively analysed. Stucki et al. (2012) and Froidevaux and Martius (2016) both looked at atmospheric precursors of extreme floods, and Giannakaki and Martius (2016) discussed the weather patterns associated with intense precipitation events. Helbling et al. (2006) and Diezig and Weingartner (2007) assessed the role of different flood drivers across Swiss catchments, like extreme or continuous rainfall, rain on snow events, and snow and/or glacier melt. Finally, Froidevaux et al. (2015) quantified the influence of accumulated precipitation before flood events in Switzerland in an analysis of annual discharge peaks across 101 catchments. They showed that short-range antecedent precipitation, up to three days before an event, was the most relevant predictor of flood occurrence and magnitude. Long-range antecedent precipitation, from 4 days to a month before an event, was nevertheless still relevant for the Jura mountains and parts of the Swiss Plateau. However, it is unclear whether these conclusions still hold in the case of persistent or recurrent flood conditions, characterized by repeated exceedances of daily discharge percentiles over short

https://doi.org/10.5194/nhess-2021-93
Preprint. Discussion started: 6 April 2021

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time windows. The hydrological response to multiple extreme precipitation events occurring as part of a cluster may also differ from the response to the same events separated by longer time periods, as evidenced by the results of (Paschalis et al., 2014) who showed that flood peaks were strongly shaped by antecedent soil wetness conditions, itself largely affected by the temporal correlation of precipitation. In addition, in basins with high retention capacities (*e.g.*, with natural or artificial lakes), single extreme precipitation events may not be enough to trigger floods, which require instead prolonged periods of heavy precipitation.

The goals of this study are therefore twofold. First, we aim to quantify the sub-seasonal clustering of precipitation extremes in time across Switzerland. We take the same approach as Barton et al. (2016) and Tuel and Martius (2021) which relies on Ripley's K function as an indicator of clustering, and analyse each season separately to remove the seasonal signal in extreme precipitation magnitude. We discuss the patterns and robustness of the spatio-temporal distribution of sub-seasonal clustering at the scale of $\approx$ 1000 km^2 catchments covering the whole of Switzerland. Second, we evaluate the links between extreme precipitation clusters, extreme precipitation accumulations and persistent flood events using observed discharge data from 93 catchments. Section 2 introduces the data and outlines the methods used in this study. Results are presented in section 3 and discussed in section 4, before concluding in section 5.

2 Data and methods

2.1 Datasets

Reference precipitation data for this study comes from the daily 2x2km RhiresD dataset. RhiresD, developed by MeteoSwiss, covers the 1961-today period and is obtained by spatial interpolation of data from a high-density rain-gauge network that extends across Switzerland, with at least 420 stations available for any single day. The effective scale of RhiresD varies as a function of station density, but on average is of the order of 15-20 km, the typical inter-station distance. A detailed description of this dataset can be found in Frei and Schär (1998). We average RhiresD data over a hydrological partitioning of Switzerland that consists of 63 catchments with a mean area of 900 km^2 (see Figure 4). Catchment-scale aggregation is useful to identify the occurrence of high-impact heavy precipitation events, and also to smoothe RhiresD data to a lower resolution more consistent with its effective resolution. This partitioning is used here with no relation to its hydrological meaning, simply to divide the whole of Switzerland into simple units. In particular, it is independent of the catchments defined by the location of the river discharge observations, which do not cover the whole country (see below).

For purposes of comparison, we also consider other daily precipitation datasets, at their native resolutions: ERA5 (Hersbach et al., 2020), the latest ECMWF reanalysis available from 1979 onwards at 0.25° resolution, in which precipitation is a forecasted quantity, *i.e.* not directly constrained by assimilated observations; the satellite-based TRMM TMPA (TRMM Multi-Satellite Precipitation Analysis) 3B42 version 7 (50°S-50°N, 1998-2019, 0.25° resolution) (Huffman et al., 2007), CMORPH (60°S-60°N, 2003-2019, 0.25° resolution) (Joyce et al., 2004) and GPCP One-Degree Daily (1DD) version 1.2 (40°S-40°N, 1997-2019, 1° resolution) (Huffman et al., 2001); and the land-only, station-based Climate Prediction Center Global Unified

https://doi.org/10.5194/nhess-2021-93
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Gauge-Based Analysis of Daily Precipitation (1979-2019, 0.5° resolution) (Chen et al., 2008) and EOBS gridded product version 19.0e (1950-2019, 0.25° resolution) (Haylock et al., 2008).

We analyse daily discharge observations for 93 small to medium-sized catchments (14-1700 km^2) distributed across Switzerland (Figure 1). These cover a wide variety of catchment characteristics and climates, from glacial and nival runoff regimes at high altitudes to pluvial regimes in the Swiss plateau (see Muelchi et al. (2021) for details on the catchment characteristics). The data for each catchment range from January 1961 to December 2017; the proportion of catchments with data rises from about 45% in the early 1960s to more than 95% in 1995, at which level it remains until 2015, before rapidly decreasing to 30% by the end of 2017. For each catchment, the analysis is conducted over the period for which discharge data is available. This means that daily discharge percentiles (and precipitation percentiles, when precipitation and discharge are considered together) are calculated over different time periods depending on the catchment.

2.2 Methods

2.2.1 Sub-seasonal temporal clustering of precipitation

For each dataset, precipitation extremes are defined on a monthly basis as as days that exceed the 99^{th} all-day percentiles. Events within each season (winter: DJF; spring: MAM; summer: JJA; and fall: SON) are then analysed together. Trends in extreme daily precipitation percentiles are not taken into account. Taking monthly percentiles, as in Barton et al. (2016), allows to remove the influence of the seasonality in extreme precipitation magnitude. As a result, the rate of occurrence of extreme precipitation events is somewhat constant across the year, which makes it possible to assess the statistical significance of clustering at sub-seasonal timescales. As the individual weather systems associated with extreme precipitation in each season may sometimes last for a few days, the short-term temporal dependence in daily precipitation above extreme quantiles is removed by way of a standard runs declustering procedure (Coles, 2001) with length $r = 2$ days, well-suited for Switzerland Barton et al. (2016).

The temporal clustering of precipitation extremes is then assessed using Ripley's K function (Ripley, 1981). We give here a quick overview of the methodology and refer the reader to Tuel and Martius (2021) for further details. Applied to a time series, Ripley's K function for a given window size n measures the average number of extreme events in a neighbourhood of n days before and after a random extreme event in the series. This gives information about the tendency toward temporal clustering in the time series. The larger the value of Ripley's K function for a given n, the more clustered the extremes. The significance of temporal clustering is tested by comparing its Ripley's K values to those obtained for a Monte-Carlo sample of 5000 simulated homogeneous Poisson processes with the same average event density as the sample series. In homogeneous Poisson processes, events occur independently from each other and therefore exhibit complete temporal randomness. This procedure yields an empirical p-value for the significance at any n. As we deal with multiple hypothesis tests, we implement a false discovery rate procedure (Wilks, 2016) with a baseline significance level of 5% to identify catchments where clustering is significant. Results are summarized across four timescales: 5-15, 15-25, 25-35 and 35-45 days; clustering is said to be significant for a given time interval if it is significant for at least half of n values in that interval.

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2.2.2 Identification of cluster events

Individual extreme precipitation clusters are identified with the automatic algorithm of Kopp et al. (2021). Starting from the declustered binary extreme event series, we calculate the 21-day moving sum of extreme events. The 21-day period with the largest sum is selected if that sum is larger than 2. In the case of multiple periods with the same number of extreme events, the one with the largest precipitation accumulation is selected first. The extreme events included in the selected cluster are then removed from the original series, and the procedure is run again to identify the next cluster. This avoids overlap between selected events. The choice of the 21-day time window is well-suited to quantify clustering at sub-seasonal timescales, and is generally consistent with the length of observed cluster episodes that led to major floods in Switzerland (see introduction). Results do not differ significantly for slightly shorter or longer (2-4 weeks) windows.

2.2.3 Flood events

Flood days are identified at each of the 93 catchments as all days when discharge exceeds its extreme annual percentile value (95^{th} and 99^{th} percentiles are analysed separately). Unlike precipitation, we use annual percentiles since they are more relevant in terms of impacts. Persistent flood events are defined as periods of fixed length L containing at least N flood days. We consider three sets of values: $(L,N) \in \{(5,10),(8,20),(10,30)\}$. Depending on the values of L and N, no events may occur in some catchments, in which case they are simply excluded from the corresponding analysis.

3 Results

Before describing the results, we briefly discuss the seasonality of heavy precipitation and floods at the catchment scale. For this we show the seasonal distribution of exceedances of the annual 99^{th} percentile of daily precpitation and discharge. Heavy precipitation is most frequent during summer and fall over most of Switzerland (Figure 2) (Helbling et al., 2006; Diezig and Weingartner, 2007; Panziera et al., 2018). The peak occurs in summer for the Swiss Plateau and the Alps, and in fall for the Ticino area and the Jura (Isotta et al., 2014) (Figure 2-c,d). The seasonality is most pronounced at low elevations, particularly over the Plateau where the summer season concentrates up to 60% of extreme precipitation events. By contrast, over the Jura and the Alpine Ridge, winter and spring each account for about 20% of extreme precipitation events, and summer around 30-40%. This seasonality is rooted in dynamical and thermodynamical constraints. Extreme precipitation requires sustained convergence and lifting of moist air, which in Switzerland is often achieved by forced orographic ascent of moisture-laden flow. Combinations of enhanced westerly winds and Atlantic water vapour transport, conducive to heavy precipitation over the northern half of Switzerland, occur most frequently in summer and fall (Giannakaki and Martius, 2016). On the southern side of the Alps, extreme precipitation is linked to the southerly advection of moist Mediterranean air caused by upper-level troughs. These are connected to potential vorticity (PV) streamers or cut-offs centred west of the Alps, which are most frequent during fall (Martius et al., 2006). In addition to these large-scale considerations, lifting forced by local convective instability during summer also favours heavy precipitation (Stucki et al., 2012).

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Flood occurrence also strongly varies over time and space (Figure 3). Alpine catchments with high elevations typically reach their most extreme discharge values during summer, mainly due to snow- and glacier melt, but also to heavier precipitation intensities (Figure 2-c). Conversely, over the smaller Jura mountains, floods are most frequent in winter and spring, due to a combination of saturated or frozen soils, relatively large extreme precipitation magnitude (Figure 2-a,b) and a smaller snow-to-rain ratio compared to the Alps. In summer and fall, despite slightly heavier precipitation extremes, floods are rare, as evapotranspiration is higher and soils less saturated than in the cold season. In catchments located on the Swiss Plateau, floods are generally equally likely between winter, spring and summer, and rare during the fall season. The Ticino area is the only region where flood occurrence peaks in fall (50-60% of flood events), which is also the season with the heaviest precipitation (Figure 2-d).

Surface conditions, like soil saturation, presence of snow/ice, vegetation cover, or evaporative demand, vary substantially from one season to the next. Hence the discharge response to a same heavy precipitation magnitude may differ depending on the season. Combined with the seasonality in extreme precipitation, it supports our defining extreme precipitation on a monthly instead of an annual basis.

3.1 Seasonal cycle of clustering significance

We now turn to the analysis of Ripley's K values and their implications in terms of sub-seasonal temporal clustering. Several coherent areas exhibit K values that are significantly larger than those expected for homogeneous Poisson processes with no temporal dependence (Figures 4 and 5). In winter, significant temporal clustering of precipitation extremes is generally found along the Alpine ridge, concentrated at the 15-25 and 25-35 day timescales (5-a and b). In spring, two catchments in Northern Switzerland as well as a few catchments in Southeastern Switzerland also exhibit significant clustering (5-c and d). By contrast, results for the summer season show a complete absence of temporal clustering significance (5-e and f). Finally, in fall, significance is found at all timescales over both the western tip of Switzerland and the southern side of the Alps (5-g and h).

Similar patterns are found by comparing to the coarser-resolution precipitation datasets (ERA5, TRMM, EOBS, CPC and CMORPH, with some notable exceptions. Clustering significance over the Alps in winter is also present in the coarser-resolution data (Figure 6-a). In spring, however, there are no signs of significant temporal clustering anywhere in Switzerland, including along the northern and southern borders where significance was found in RhiresD (Figure 6-b). All the datasets agree nevertheless on the absence of clustering in summer (Figure 6-c), and on significant clustering in southern and south-eastern Switzerland during the fall season (Figure 6-d). Temporal clustering does not appear particularly significant, however, in western Switzerland during fall. This regional approach allows to highlight the strong spatial coherence in the clustering significance patterns. In winter, clustering significance extends over a large region stretching from the Mont Blanc massif in France to eastern Switzerland along the Alpine ridge, in good agreement with RhiresD (Figures 5-a and 6-a). Similarly, southern Switzerland is part of a larger region exhibiting significant clustering, encompassing northern Lombardy and possibly extending southwards to the Mediterranean shore (Figure 6-d).

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3.2 Cluster event characteristics

The previous statistical analysis identifies regions with a tendency to temporal clustering of precipitation extremes. By taking an event-based approach and identifying individual cluster events over 21-day periods, we can estimate average metrics for these events, like the number of extremes or total event precipitation. From the perspective of surface impacts, two potentially relevant metrics are the average contribution of clusters to seasonal precipitation and their contribution to extreme precipitation accumulations. Results for these two metrics are broadly consistent with the statistical analysis of section 3.1. In winter, extreme precipitation clusters contribute an average of ≈10% to total winter precipitation along the Alpine ridge where clustering is statistically significant (Figure 7-a). Additionally, about 60-70% of extreme 21-day precipitation accumulations (larger than the corresponding 99$^{\mathrm{th}}$ percentile) occur at the same time as clusters of extreme precipitation (Figure 8-a). Elsewhere, clusters contribute little both to seasonal and extreme precipitation accumulations. Cluster contribution to spring precipitation is generally weak, even for the catchments exhibiting clustering significance in RhiresD (Figure 7-b). Yet, clusters seem strongly linked to extreme 21-day accumulations over Western Switzerland (Figure 8-b). Consistent with the absence of clustering at that time of the year, clusters are not contributing much to summer precipitation. Finally, in fall, cluster contribution to seasonal precipitation reaches maxima of 12-16% in Southeastern Switzerland, and remains high (≥10%) in Western Switzerland as well (Figure 7-d). In Southeastern Switzerland in particular, clusters occur almost always in conjunction with extreme precipitation accumulations (Figure 8-d). Since floods in this area are most common during fall, this suggests a possibly important role of extreme precipitation clusters in high-impact weather events in this region and at that time of the year.

3.3 Extreme precipitation clusters and persistent floods

To assess the link between clusters of precipitation extremes and persistent floods, we begin by considering precipitation data during persistent flood events and in the 10 days before. Unsurprisingly, persistent floods, regardless of L and N values, are systematically associated with extreme precipitation accumulations for catchments with mean elevations up to about 1500m (Figures 9-a,b and 10-a), a clear sign of the glacial/nival runoff regime dominance above that altitude. By contrast, extreme precipitation clusters precede persistent flood events chiefly in the Ticino area of southern Switzerland and locally over the eastern parts of the Swiss Plateau and the Jura (Figure 9-c,d). The dependence to catchment elevation is similar, with a much weaker intersection of cluster events and floods at high elevations, but less robust with a larger spread of values at low elevations (Figure 10-b).

An interesting question is whether the discharge response at the catchment scale after an extreme precipitation event differs between single extreme events and events that are part of clusters. Figure 11 shows that it is indeed the case for most catchments, particularly those below 1500m elevation. In the five days following an extreme precipitation event, the fraction of days exceeding either the 95$^{\mathrm{th}}$ or the 99$^{\mathrm{th}}$ percentiles of daily discharge is larger when that event belongs to a cluster. The difference is particularly large over northern Switzerland and in the Ticino area where, for instance, the 99$^{\mathrm{th}}$ percentile of daily discharge values is exceeded on average 20-30% of the time in the days following an extreme precipitation event during a cluster, but only 10-15% if the extreme occurred outside of a cluster. The occurrence of a cluster of precipitation extremes greatly increases

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the likelihood of high-discharge events, particularly at low elevations (Figure 12). A "reference" flood day probability can be estimated for each catchment by first identifying cluster events and then calculating the flood probability for the days of the year during which clusters were observed, using data from all available years. Doing so, we find that daily discharge is more than 7 (respectively 10) times more likely to exceed its 95^{th} (respectively 99^{th}) percentile during and after a cluster in Northeastern Switzerland, for instance. The analysis of the distribution of daily discharge percentiles around the time of occurrence of extreme precipitation events confirms these results: while the probability of observing a flood on the day following an extreme event is not very different between clustered and non-clustered extremes, that probability decreases much faster in the days following non-clustered extremes (Figure 13).

4 Discussion

4.1 Patterns of clustering significance and their physical interpretation

Section 3.1 showed that clustering significance was found mainly over the Alpine ridge during winter and in southern and southeastern Switzerland during fall. The robustness of the results over these two regions across timescales and datasets suggests that specific physical processes are responsible for the clustering. Our definition of extreme precipitation events based on the exceedance of monthly percentiles of daily precipitation removes the influence of seasonality in extreme precipitation magnitude (Figure 2). By applying Ripley's K function to the resulting time series, we can thus focus on short-term temporal dependence in extreme precipitation occurrence driven by sub-seasonal dynamics or intra-annual variability (*e.g.*, climate modes). It is therefore interesting to speculate about what the physical drivers of clustering may be.

Whether in winter or in fall, clustering significance is chiefly concentrated at timescales below 30 days, which seems to preclude any dominant role of seasonal SST anomalies. During winter, extreme precipitation events in northern Switzerland usually occur in connection with high IVT structures, like atmospheric rivers, and the associated extreme water vapour transport converging onto the orography (Froidevaux and Martius, 2016; Giannakaki and Martius, 2016). The concentration of clustering significance over the Alps possibly results from a spatial anchoring of precipitation at high elevations, through orographic lifting and convergence, during an atmospheric river event, while precipitation in the lower-lying area is spatially more dependent on the presence of cold-air pools upstream of the mountains. Over the Euro-Atlantic sector, cyclonic weather regimes and their strong westerlies favour the occurrence of atmospheric rivers in Western Europe (Pasquier et al., 2019). The North Atlantic Oscillation (NAO) also modulates the frequency of atmospheric rivers (Zavadoff and Kirtman, 2020), but its relevance for Switzerland remains unclear (Yang and Villarini, 2019).

During fall, several major clusters of precipitation extremes were related to recurrent Rossby wave breaking over western and southwestern Europe (Barton et al., 2016), the resulting PV anomalies leading to enhanced low-level moisture transport from the Mediterranean towards the Alps (Martius et al., 2006). Why wave breaking would be recurrent in this region and at that time of the year remains unclear. Recurrent cyclogenesis and extratropical transition of tropical cyclones upstream over the western Atlantic seem to play a role, but not necessarily a systematic one. Persistence in blocking conditions in the northwestern Atlantic also contributed to upper-level wave amplification and the subsequent occurrence of precipitation extreme clusters in Southern Switzerland (Barton et al., 2016).

The apparent lack of agreement among precipitation datasets regarding the significance of the clustering over western Switzerland in fall (Figures 5-g,h and 6-d) is less straightforward to interpret. Despite the precautions taken to control the false discovery rate, it is still possible that significance in this region is detected by pure chance. Yet, it is not altogether obvious that the gridded satellite or reanalysis datasets are completely reliable either. If thunderstorms are responsible for many extreme precipitation events their representation in reanalysis products can be questioned. Their small spatial scale may also cause them to be missed in satellite products. While coarse-resolution gridded datasets seem to agree on the timing and magnitude of precipitation extremes in western Switzerland during fall (Rivoire et al., 2021), a more detailed comparison with RhiresD data and an analysis of the type of events responsible for these extremes would be required to conclude.

4.2 Relevance of extreme precipitation clusters for flood risk

Frequent clusters leading to extreme precipitation accumulations are likely to be an important precursor of major flood events in southern Switzerland. We saw that persistent floods at elevations lower than 1500m a.s.l. are almost systematically associated with extreme precipitation accumulations in the days preceding such events (Figure 9-a,b). This is consistent with the runoff regimes at lower elevations, as well as with the results of Froidevaux et al. (2015). Such accumulations are not always the consequence of clusters of extremes, however. Outside southern Switzerland during fall, western Switzerland during spring and, to a lesser extent, Alpine catchments during winter, the overlap of cluster events and extreme precipitation accumulations is generally smaller than 50%, and often smaller than 25% (Figure 8). Results in summer and spring can be understood by the scarceness of cluster events in those seasons. In winter, despite being frequent, clusters over the Alps are less systematically associated with extreme accumulations, which are often the result of a single heavy precipitation event.

Still, from the perspective of surface impacts, clusters remain relevant, regardless of their overall frequency, if they increase flood risk. Across catchments, clustered extremes appear linked to more likely and more persistent flood conditions than single extremes (Figures 10 and 11). The difference is quite high for the Ticino area (*e.g.*, Figure 10-c,d), possibly due to the fact that floods in this area generally occur in the fall, when clusters bring higher daily precipitation than single extremes (Figure 8-d). Additionally, the first extreme in a cluster event is likely to increase soil moisture, which in turn will enhance the discharge response to the subsequent precipitation extremes. This may explain why flood recession timescales appear noticeably longer after clustered extremes than after single extremes (Figure 13).

Finally, the case of Western Switzerland during spring is interesting. Though rare, clusters are responsible for almost all extreme precipitation accumulations (Figure 8-b). Over this region, floods are somewhat less frequent in spring than in winter (Figure 3-a,b). Yet, spring floods can still be quite devastating, since precipitation generally falls as rain instead of snow, and limited vegetation cover makes erosion more likely. From a risk perspective, cluster events that affect Western Switzerland during spring may deserve further attention.

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4.3 Some limitations and future prospects

Our approach to quantify links between clustered extremes and flood response has a number of limitations. First, we based our analysis on the exceedance of given precipitation and discharge percentiles, not taking into account either flood volumes or precipitation intensities. This is naturally quite restrictive, and in particular fails to capture potential non-linearities in relationships above the selected percentiles. In addition, spatial variability in extreme discharge or average total cluster precipitation were not analysed.

An accurate quantification of risk also relies on combining hazards, exposure and vulnerability. Results from this study are heavily biased towards hazards, while exposure and vulnerability may differ substantially between catchments, due to variability in population density, infrastructure, flood management capacities, etc. As a result, "climate risk" may be high, but exposure and vulnerability low, leading to medium overall risk levels. Similarly, we did not take into account the influence of catchment regulation in this work. While the analysed catchments are generally not heavily regulated ones, human influence may still be felt, especially when it results in the smoothing over time of extreme flow conditions, which would impact our analysis of persistent flood events.

Finally, our definition of floods and flooding persistence was also somewhat simplistic. First, while from the perspective of impacts it makes sense to define floods based on annual discharge percentiles, in snow-driven or glaciated catchments, this choice tends to discard potential high-flow conditions occurring outside summer, that do not exceed summer peak discharge but which can still be damaging. Second, our definition of flooding persistence based on a minimal number of flood days in a given time window lumps together single, long floods and recurrent short ones, two kinds of events with potentially different impacts, and which may have to be managed differently.

5 Conclusions

The main findings of this study are as follows. First, we identified a specific seasonal and spatial pattern of significance in sub-seasonal temporal clustering of extreme precipitation events across Switzerland. Clustering is most significant over the Alps in winter and Southern Switzerland during fall. Second, extreme precipitation clusters play a contrasted role in seasonal and sub-seasonal extreme precipitation accumulations. Their contribution is particularly high in fall over southern Switzerland, but more limited over the Alps in winter. Clusters are also frequently associated with extreme precipitation accumulations over Western Switzerland during spring, despite their relative scarcity. Finally, cluster events, regardless of their frequency, are generally associated with a higher flood likelihood and more persistent flood conditions over much of Switzerland. The region that stands out from this analysis is the Ticino area in Southern Switzerland. There, clusters of precipitation extremes are frequent during fall and tend to bring particularly large amounts of precipitation. As a result, they appear to be critical precursors of major flood events, a conclusion supported by previous event-based analyses. While our results are exclusively focused on Switzerland, the method adopted for this analysis could in principle be applied to other regions of the world to quantify the relevance of temporal heavy precipitation clusters for flood risk.

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Data availability. The RhiresD dataset is provided by MeteoSwiss, the Swiss Federal Office of Meteorology and Climatology. Discharge data were obtained from Switzerland's Federal Office for the Environment. ERA5 reanalysis data for the 1979-2019 period are available from https://apps.ecmwf.int/datasets/. TRMM data can be downloaded at https://disc.gsfc.nasa.gov/datasets/TRMM_3B42_Daily_7/summary. CMORPH and GPCP data are provided by NOAA's National Centers for Environmental Information at respectively https://www.ncei.noaa.gov/data/cmorph-high-resolution-global-precipitation-estimates/access/daily/0.25deg/ and https://www.ncei.noaa.gov/data/global-precipitation-climatology-project-gpcp-daily/access/. CPC Global Unified Precipitation data is provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov/.

Author contributions. O.M. designed and supervised the research. A.T. designed the research, implemented the code, analysed the data and provided the figures; A.T. and O.M. wrote the manuscript.

Competing interests. The authors declare no competing interests.

Acknowledgements. The authors gratefully acknowledge the Swiss Federal Office of the Environment (FOEN) and Regula Mülchi for the Swiss river discharge data. O.M. acknowledges support from the Swiss Science Foundation (SNSF) grant number 178751.

https://doi.org/10.5194/nhess-2021-93
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References

BAFU: Umgang mit Naturgefahren - Bericht des Bundesrats in Erfüllung des Postulats 12.4271 Darbellay vom 14.12.2012, Tech. rep., Bundesamt für Umwelt (BAFU), Bern, https://scnat.ch/de/uuid/i/ccaaec15-1b96-57e7-b36d-db5f12864c28-Umgang{_}mit{_}Naturgefahren{_}in{_}der{_}Schweiz, 2016.

BAFU and WSL: Ereignisanalyse Hochwasser 2005 Teil 2 - Analyse von Prozessen, Massnahmen und Gefahrengrundlagen, Tech. rep., Bundesamt für Umwelt (BAFU), Bern, https://www.bafu.admin.ch/bafu/de/home/themen/naturgefahren/publikationen-studien/publikationen/ereignisanalyse-hochwasser-2005-analyse-von-prozessen-massnahmen-und-gefahrengrundlagen.html, 2008.

Barton, Y., Giannakaki, P., von Waldow, H., Chevalier, C., Pfahl, S., and Martius, O.: Clustering of Regional-Scale Extreme Precipitation Events in Southern Switzerland, Monthly Weather Review, 144, 347–369, https://doi.org/10.1175/MWR-D-15-0205.1, 2016.

Blackburn, M., Methven, J., and Roberts, N.: Large-scale context for the UK floods in summer 2007, Weather, 63, 280–288, https://doi.org/10.1002/wea.322, 2008.

Chen, M., Shi, W., Xie, P., Silva, V. B. S., Kousky, V. E., Wayne Higgins, R., and Janowiak, J. E.: Assessing objective techniques for gauge-based analyses of global daily precipitation, Journal of Geophysical Research, 113, D04 110, https://doi.org/10.1029/2007JD009132, 2008.

Coles, S.: An Introduction to Statistical Modeling of Extreme Values, Springer Series in Statistics, Springer London, London, https://doi.org/10.1007/978-1-4471-3675-0, 2001.

Dacre, H. F. and Pinto, J. G.: Serial clustering of extratropical cyclones: a review of where, when and why it occurs, npj Climate and Atmospheric Science, 3, 48, https://doi.org/10.1038/s41612-020-00152-9, 2020.

Diezig, R. and Weingartner, R.: Hochwasserprozesstypen: Schlüssel zur Hochwasserabschätzung, Wasser und Abfall, 4, 18–26, 2007.

Doswell, C. A., Brooks, H. E., and Maddox, R. A.: Flash Flood Forecasting: An Ingredients-Based Methodology, Weather and Forecasting, 11, 560–581, https://doi.org/10.1175/1520-0434(1996)011<0560:FFFAIB>2.0.CO;2, 1996.

Frei, C. and Schär, C.: A precipitation climatology of the Alps from high-resolution rain-gauge observations, International Journal of Climatology, 18, 873–900, https://doi.org/10.1002/(SICI)1097-0088(19980630)18:8<873::AID-JOC255>3.0.CO;2-9, 1998.

Froidevaux, P. and Martius, O.: Exceptional integrated vapour transport toward orography: an important precursor to severe floods in Switzerland, Quarterly Journal of the Royal Meteorological Society, 142, 1997–2012, https://doi.org/10.1002/qj.2793, 2016.

Froidevaux, P., Schwanbeck, J., Weingartner, R., Chevalier, C., and Martius, O.: Flood triggering in Switzerland: the role of daily to monthly preceding precipitation, Hydrology and Earth System Sciences, 19, 3903–3924, https://doi.org/10.5194/hess-19-3903-2015, 2015.

Giannakaki, P. and Martius, O.: Synoptic-scale flow structures associated with extreme precipitation events in northern Switzerland, International Journal of Climatology, 36, 2497–2515, https://doi.org/10.1002/joc.4508, 2016.

Grams, C. M., Binder, H., Pfahl, S., Piaget, N., and Wernli, H.: Atmospheric processes triggering the central European floods in June 2013, Natural Hazards and Earth System Sciences, 14, 1691–1702, https://doi.org/10.5194/nhess-14-1691-2014, 2014.

Guzzetti, F., Peruccacci, S., Rossi, M., and Stark, C. P.: Rainfall thresholds for the initiation of landslides in central and southern Europe, Meteorology and Atmospheric Physics, 98, 239–267, https://doi.org/10.1007/s00703-007-0262-7, 2007.

Haylock, M. R., Hofstra, N., Klein Tank, A. M. G., Klok, E. J., Jones, P. D., and New, M.: A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006, Journal of Geophysical Research, 113, D20 119, https://doi.org/10.1029/2008JD010201, 2008.

https://doi.org/10.5194/nhess-2021-93
Preprint. Discussion started: 6 April 2021

Natural Hazards and Earth System Sciences
Discussions

Helbling, A., Kan, C., and Vogt, S.: Dauerregen, Schauer oder Schmelze-welche Ereignisse lösen in der Schweiz die Jahreshochwasser aus?, Wasser Energie Luft, 98, 249–254, 2006.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.: The ERA5 global reanalysis, Quarterly Journal of the Royal Meteorological Society, 146, 1999–2049, https://doi.org/10.1002/qj.3803, 2020.

Huffman, G. J., Adler, R. F., Morrissey, M. M., Bolvin, D. T., Curtis, S., Joyce, R., McGavock, B., and Susskind, J.: Global Precipitation at One-Degree Daily Resolution from Multisatellite Observations, Journal of Hydrometeorology, 2, 36–50, https://doi.org/10.1175/1525-7541(2001)002<0036:GPAODD>2.0.CO;2, 2001.

Huffman, G. J., Adler, R. F., Bolvin, D. T., Gu, G., Nelkin, E. J., Bowman, K. P., Hong, Y., Stocker, E. F., and Wolff, D. B.: The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales, Journal of Hydrometeorology, 8, 38–55, https://doi.org/10.1175/JHM560.1, 2007.

Huntingford, C., Marsh, T., Scaife, A. A., Kendon, E. J., Hannaford, J., Kay, A. L., Lockwood, M., Prudhomme, C., Reynard, N. S., Parry, S., Lowe, J. A., Screen, J. A., Ward, H. C., Roberts, M., Stott, P. A., Bell, V. A., Bailey, M., Jenkins, A., Legg, T., Otto, F. E. L., Massey, N., Schaller, N., Slingo, J., and Allen, M. R.: Potential influences on the United Kingdom's floods of winter 2013/14, Nature Climate Change, 4, 769–777, https://doi.org/10.1038/nclimate2314, 2014.

Insua-Costa, D., Miguez-Macho, G., and Llasat, M. C.: Local and remote moisture sources for extreme precipitation: a study of the two catastrophic 1982 western Mediterranean episodes, Hydrology and Earth System Sciences, 23, 3885–3900, https://doi.org/10.5194/hess-23-3885-2019, 2019.

Isotta, F. A., Frei, C., Weilguni, V., Perčec Tadić, M., Lassègues, P., Rudolf, B., Pavan, V., Cacciamani, C., Antolini, G., Ratto, S. M., Munari, M., Micheletti, S., Bonati, V., Lussana, C., Ronchi, C., Panettieri, E., Marigo, G., and Vertačnik, G.: The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data, International Journal of Climatology, 34, 1657–1675, https://doi.org/10.1002/joc.3794, 2014.

Joyce, R. J., Janowiak, J. E., Arkin, P. A., and Xie, P.: CMORPH: A Method that Produces Global Precipitation Estimates from Passive Microwave and Infrared Data at High Spatial and Temporal Resolution, Journal of Hydrometeorology, 5, 487–503, https://doi.org/10.1175/1525-7541(2004)005<0487:CAMTPG>2.0.CO;2, 2004.

Kopp, J., Rivoire, P., Ali, S. M., Barton, Y., and Martius, O.: A novel method to identify sub-seasonal clustering episodes of extreme precipitation events and their contributions to large accumulation periods, Hydrol. Earth Syst. Sci. Discuss. [preprint], 2021.

Mailier, P. J., Stephenson, D. B., Ferro, C. A. T., and Hodges, K. I.: Serial Clustering of Extratropical Cyclones, Monthly Weather Review, 134, 2224–2240, https://doi.org/10.1175/MWR3160.1, 2006.

Martius, O., Zenklusen, E., Schwierz, C., and Davies, H. C.: Episodes of alpine heavy precipitation with an overlying elongated stratospheric intrusion: a climatology, International Journal of Climatology, 26, 1149–1164, https://doi.org/10.1002/joc.1295, 2006.

Martius, O., Sodemann, H., Joos, H., Pfahl, S., Winschall, A., Croci-Maspoli, M., Graf, M., Madonna, E., Mueller, B., Schemm, S., Sedláček, J., Sprenger, M., and Wernli, H.: The role of upper-level dynamics and surface processes for the Pakistan flood of July 2010, Quarterly Journal of the Royal Meteorological Society, 139, 1780–1797, https://doi.org/10.1002/qj.2082, 2013.

Muelchi, R., Rössler, O., Schwanbeck, J., Weingartner, R., and Martius, O.: An ensemble of daily simulated runoff data (1981–2099) under climate change conditions for 93 catchments in Switzerland (Hydro-CH2018-Runoff ensemble), Geoscience Data Journal, accepted, 2021.

Panziera, L., Gabella, M., Zanini, S., Hering, A., Germann, U., and Berne, A.: A radar-based regional extreme rainfall analysis to derive the thresholds for a novel automatic alert system in Switzerland, Hydrology and Earth System Sciences, 20, 2317–2332, https://doi.org/10.5194/hess-20-2317-2016, 2016.

Panziera, L., Gabella, M., Germann, U., and Martius, O.: A 12-year radar-based climatology of daily and sub-daily extreme precipitation over the Swiss Alps, International Journal of Climatology, 38, 3749–3769, https://doi.org/10.1002/joc.5528, 2018.

Paschalis, A., Fatichi, S., Molnar, P., Rimkus, S., and Burlando, P.: On the effects of small scale space–time variability of rainfall on basin flood response, Journal of Hydrology, 514, 313–327, https://doi.org/10.1016/j.jhydrol.2014.04.014, 2014.

Pasquier, J. T., Pfahl, S., and Grams, C. M.: Modulation of Atmospheric River Occurrence and Associated Precipitation Extremes in the North Atlantic Region by European Weather Regimes, Geophysical Research Letters, 46, 1014–1023, https://doi.org/10.1029/2018GL081194, 2019.

Pinto, J. G., Bellenbaum, N., Karremann, M. K., and Della-Marta, P. M.: Serial clustering of extratropical cyclones over the North Atlantic and Europe under recent and future climate conditions, Journal of Geophysical Research: Atmospheres, 118, 12,476–12,485, https://doi.org/10.1002/2013JD020564, 2013.

Priestley, M. D. K., Pinto, J. G., Dacre, H. F., and Shaffrey, L. C.: The role of cyclone clustering during the stormy winter of 2013/2014, Weather, 72, 187–192, https://doi.org/10.1002/wea.3025, 2017.

Priestley, M. D. K., Dacre, H. F., Shaffrey, L. C., Hodges, K. I., and Pinto, J. G.: The role of serial European windstorm clustering for extreme seasonal losses as determined from multi-centennial simulations of high-resolution global climate model data, Natural Hazards and Earth System Sciences, 18, 2991–3006, https://doi.org/10.5194/nhess-18-2991-2018, 2018.

Raymond, C., Horton, R. M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J., Bowen, S. G., Camargo, S. J., Hess, J., Kornhuber, K., Oppenheimer, M., Ruane, A. C., Wahl, T., and White, K.: Understanding and managing connected extreme events, Nature Climate Change, 10, 611–621, https://doi.org/10.1038/s41558-020-0790-4, 2020.

Ripley, B. D.: Spatial Statistics, Wiley Series in Probability and Statistics, John Wiley & Sons, Inc., Hoboken, NJ, USA, https://doi.org/10.1002/0471725218, 1981.

Rivoire, P., Martius, O., and Naveau, P.: A comparison of moderate and extreme {ERA}-5 daily precipitation with two observational data sets, Earth and Space Science Open Archive ESSOAr, https://doi.org/10.1175/JCLI-D-15-0710.1, 2021.

Stucki, P., Rickli, R., Brönnimann, S., Martius, O., Wanner, H., Grebner, D., and Luterbacher, J.: Weather patterns and hydro-climatological precursors of extreme floods in Switzerland since 1868, Meteorologische Zeitschrift, 21, 531–550, https://doi.org/10.1127/0941-2948/2012/368, 2012.

Swiss Re: Floods in Switzerland – an underestimated risk, Tech. rep., Swiss Re, Zürich, https://www.planat.ch/fileadmin/PLANAT/planat{_}pdf/alle{_}2012/2011-2015/Swiss{_}Re{_}{_}Hg{_}{_}2012{_}-{_}Floods{_}in{_}Switzerland.pdf, 2012.

Tuel, A. and Martius, O.: A global perspective on the sub-seasonal clustering of precipitation extremes, in review for Weather and Climate Extremes, 2021.

van Oldenborgh, G. J., Stephenson, D. B., Sterl, A., Vautard, R., Yiou, P., Drijfhout, S. S., von Storch, H., and van den Dool, H.: Drivers of the 2013/14 winter floods in the UK, Nature Climate Change, 5, 490–491, https://doi.org/10.1038/nclimate2612, 2015.

Villarini, G., Smith, J. A., Vitolo, R., and Stephenson, D. B.: On the temporal clustering of US floods and its relationship to climate teleconnection patterns, International Journal of Climatology, 33, 629–640, https://doi.org/10.1002/joc.3458, 2013.

Vitolo, R., Stephenson, D. B., Cook, I. M., and Mitchell-Wallace, K.: Serial clustering of intense European storms, Meteorologische Zeitschrift, 18, 411–424, https://doi.org/10.1127/0941-2948/2009/0393, 2009.

Wilks, D. S.: “The Stippling Shows Statistically Significant Grid Points”: How Research Results are Routinely Overstated and Overinterpreted, and What to Do about It, Bulletin of the American Meteorological Society, 97, 2263–2273, https://doi.org/10.1175/BAMS-D-15-00267.1, 2016.

Yang, Z. and Villarini, G.: Examining the capability of reanalyses in capturing the temporal clustering of heavy precipitation across Europe, Climate Dynamics, 53, 1845–1857, https://doi.org/10.1007/s00382-019-04742-z, 2019.

Zavadoff, B. L. and Kirtman, B. P.: Dynamic and Thermodynamic Modulators of European Atmospheric Rivers, Journal of Climate, 33, 4167–4185, https://doi.org/10.1175/JCLI-D-19-0601.1, 2020.

https://doi.org/10.5194/nhess-2021-93
Preprint. Discussion started: 6 April 2021

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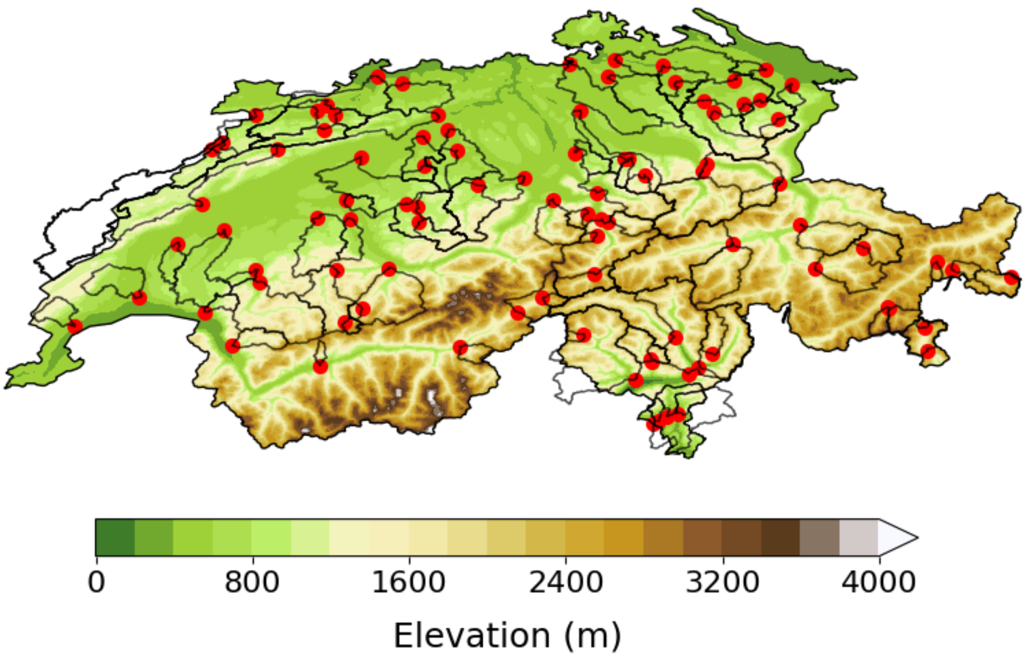

Figure 1. Topography of Switzerland (shading) and gauged catchments used in this study (black lines). Catchment outlets where discharge is measured are indicated by red dots.

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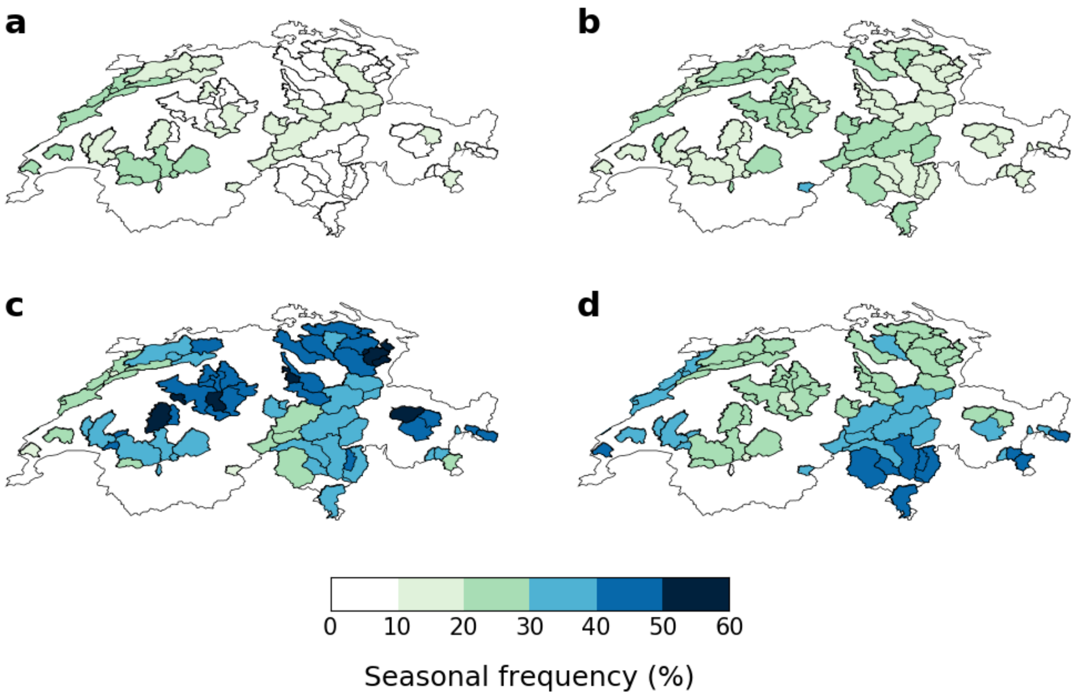

Figure 2. Seasonal frequency of extreme precipitation occurrence in RhiresD, with extreme precipitation defined based on annual 99$^{\mathrm{th}}$ percentiles of daily precipitation totals.

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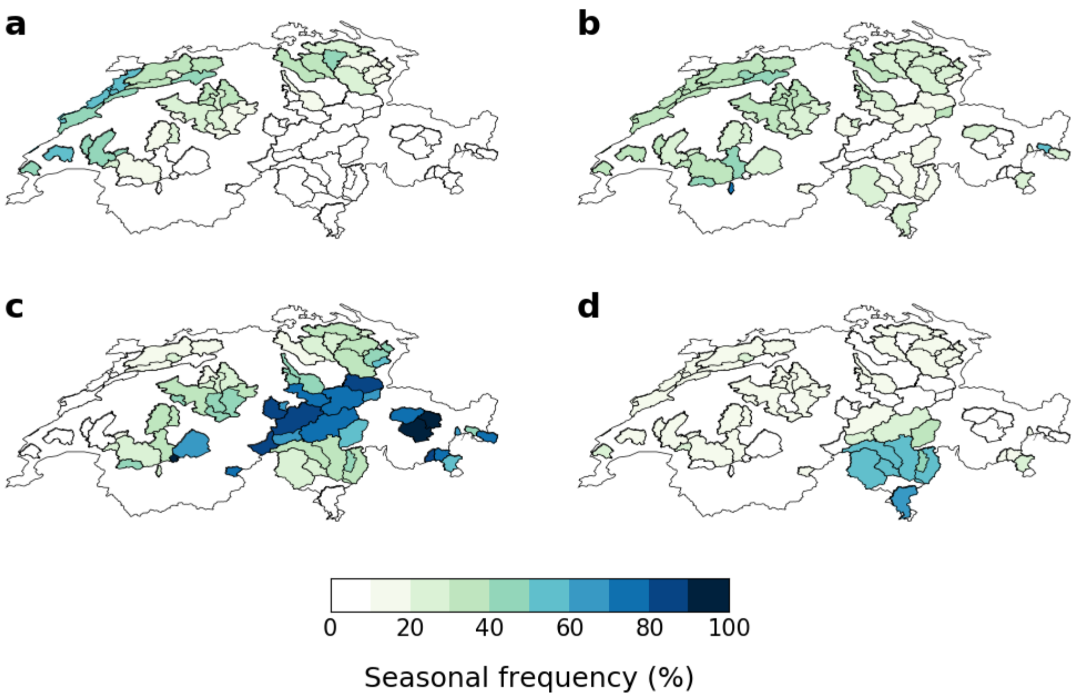

Figure 3. Seasonal frequency of flood occurrence, with floods defined based on annual 99$^{\mathrm{th}}$ percentiles of daily discharge values.

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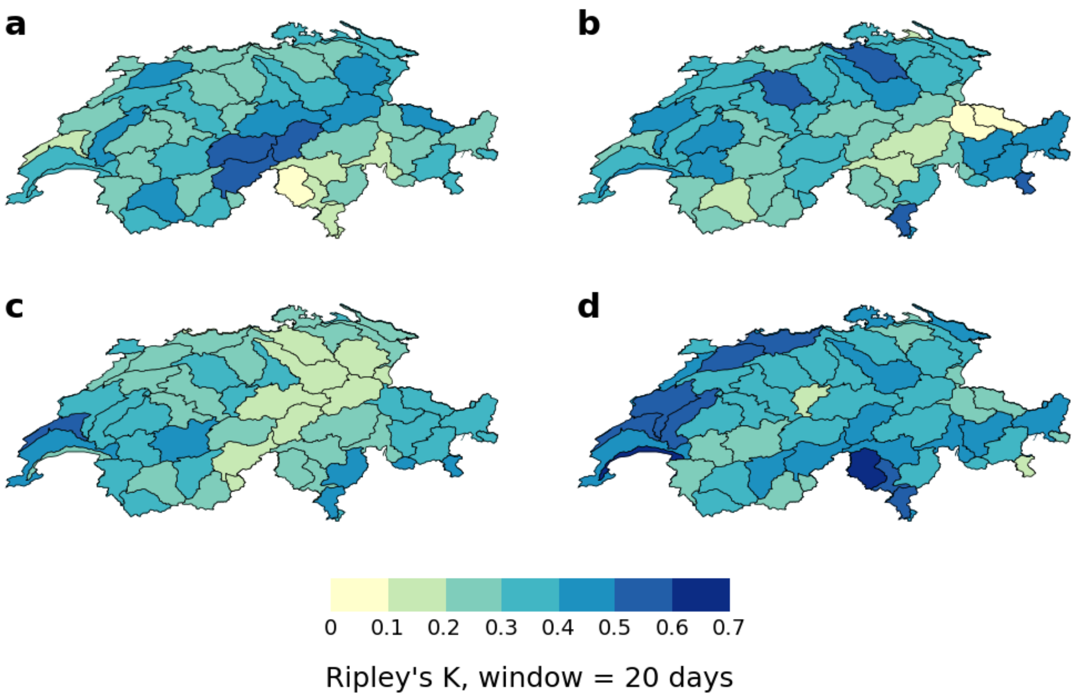

Figure 4. Value of Ripley's K in the RhiresD dataset for a 20-day window, in (a) DJF, (b) MAM, (c) JJA and (d) SON.

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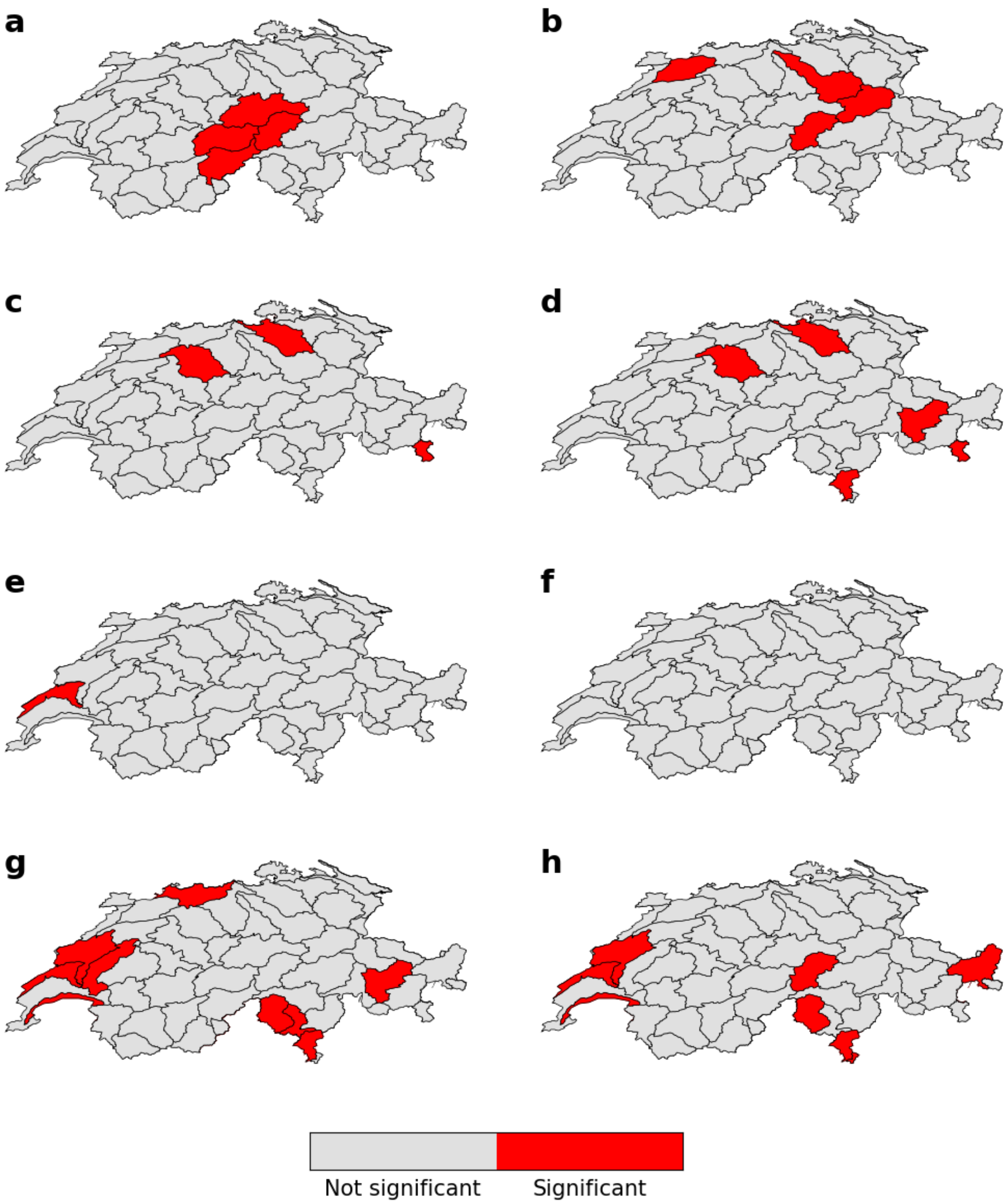

Figure 5. (a,c,e,g) Clustering significance in RhiresD for a time window of 15-25 days, in (a) DJF, (c) MAM, (e) JJA and (g) SON. (b,d,f,g) Same, but for a time window of 25-35 days.

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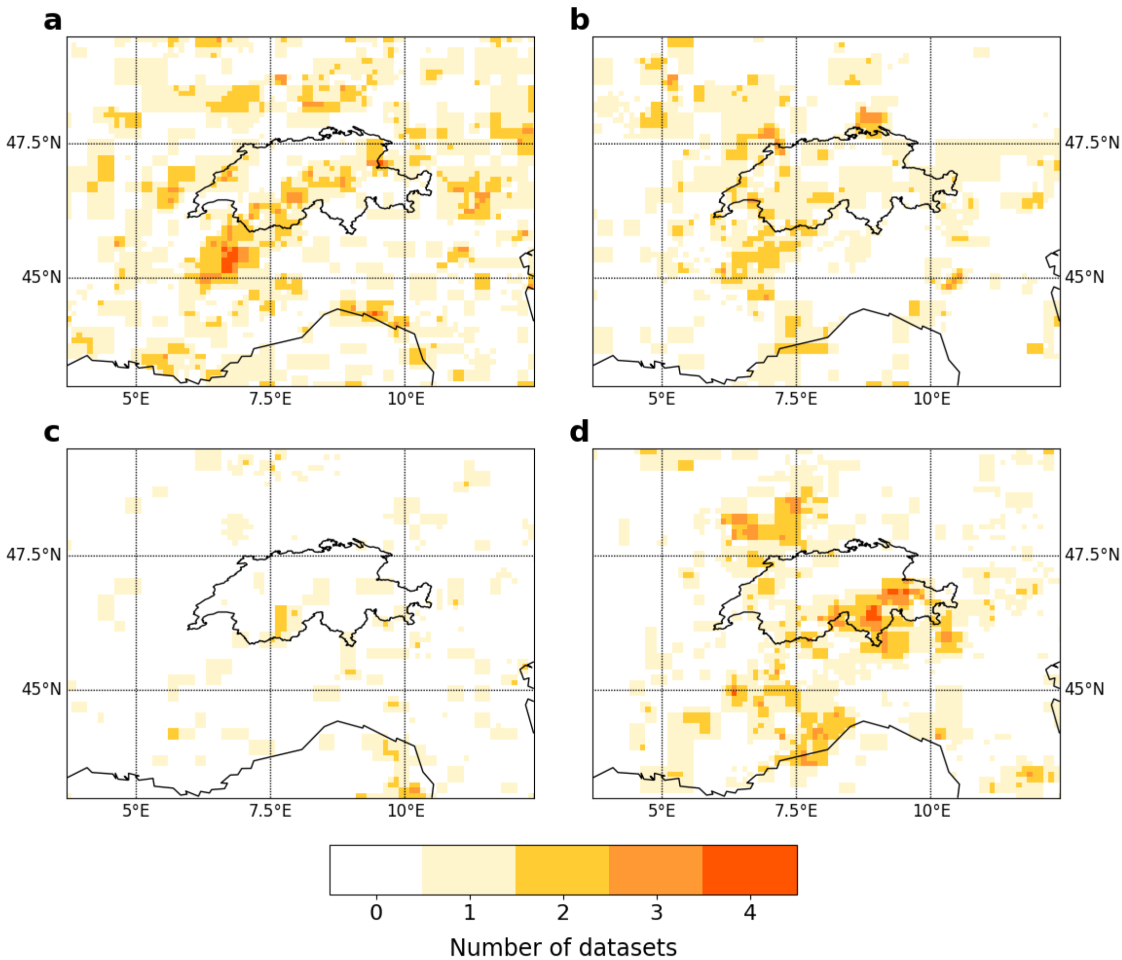

Figure 6. Number of datasets (among ERA5, TRMM, CMORPH, CPC and EOBS) that agree on the significance of extreme precipitation clustering for a 15-25 day window in (a) DJF, (b) MAM, (c) JJA and (d) SON. For this comparison, all datasets were regridded to the 0.1° EOBS resolution.

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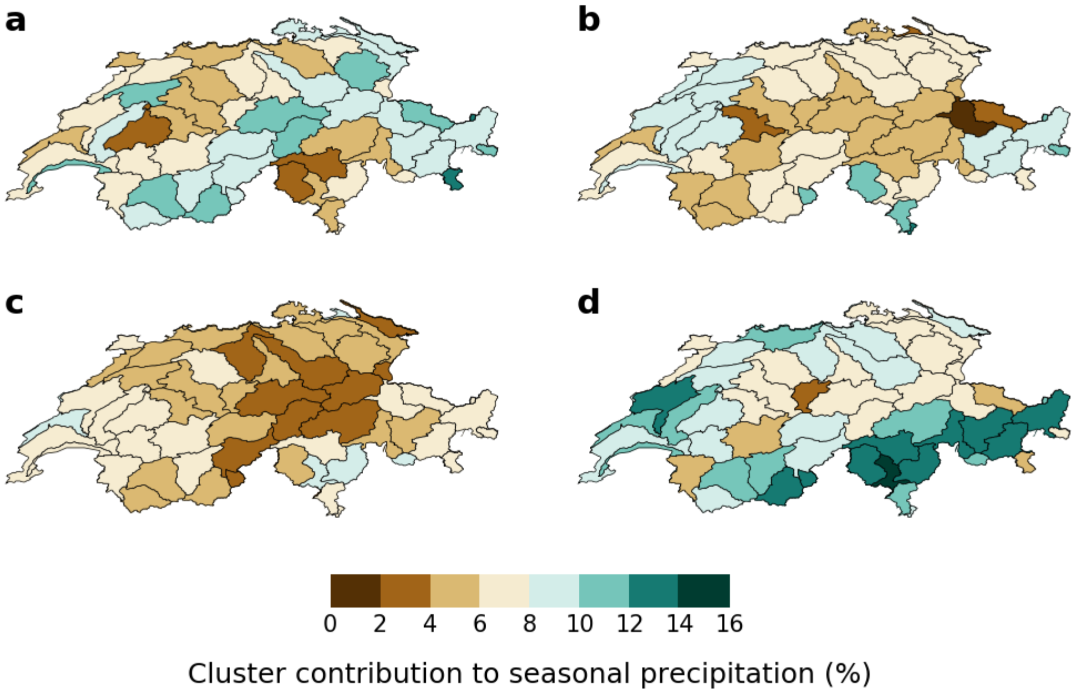

Figure 7. Contribution of 21-day extreme precipitation clusters to seasonal precipitation in RhiresD, in (a) DJF, (b) MAM, (c) JJA and (d) SON.

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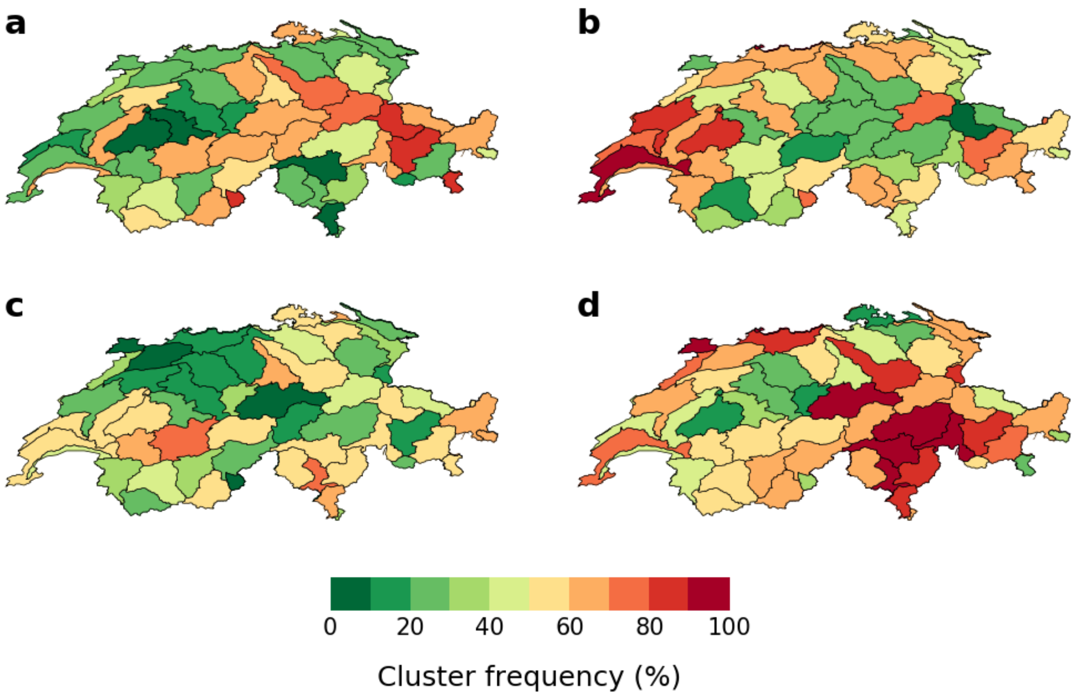

Figure 8. Frequency of extreme precipitation cluster occurrence during extreme 21-day cumulative precipitation events ($> 99^{\mathrm{th}}$ percentile) in RhiresD, in (a) DJF, (b) MAM, (c) JJA and (d) SON.

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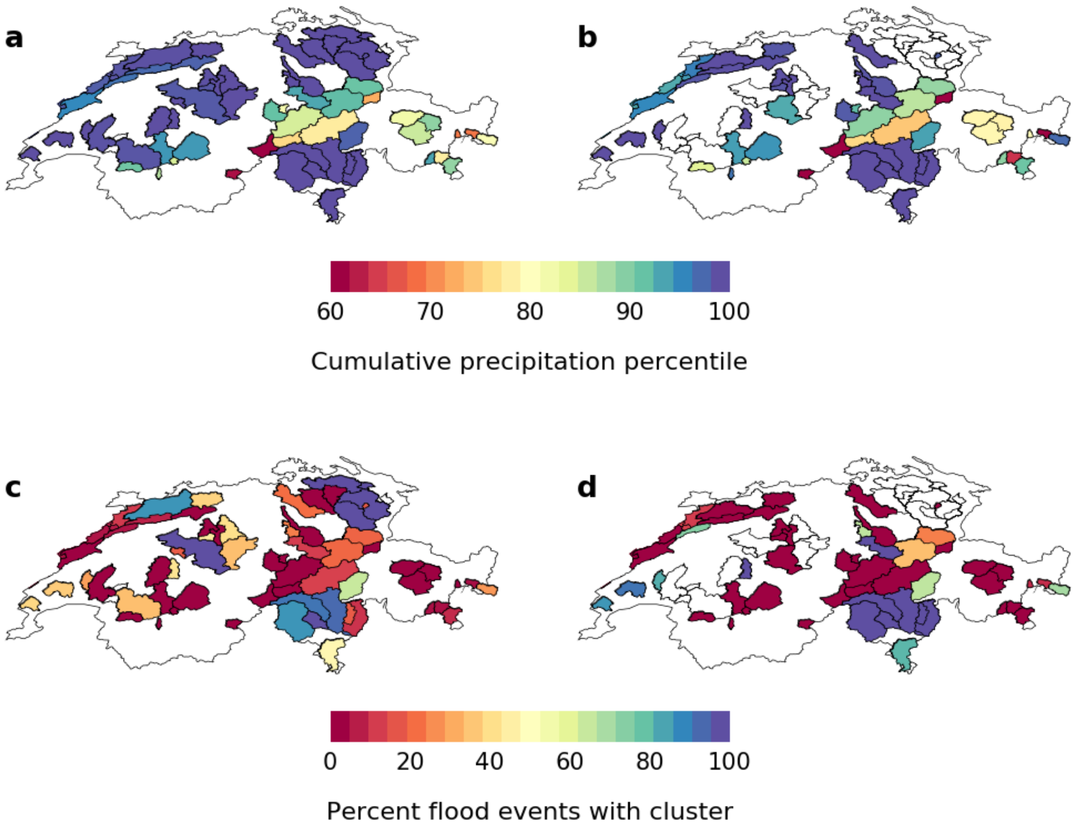

Figure 9. (a,b) Average cumulative precipitation percentile during and 10 days prior to persistent flood events, defined as: (a) at least 5 days within a 10-day window with discharge above its 99^{th} percentile, and (b) at least 8 days within a 20-day window with discharge above its 99^{th} percentile. Catchments for which such flood events are not observed are shown in white. (c,d) Same as (a,b), but for the frequency of cluster occurrence during and 10 days prior to persistent flood events

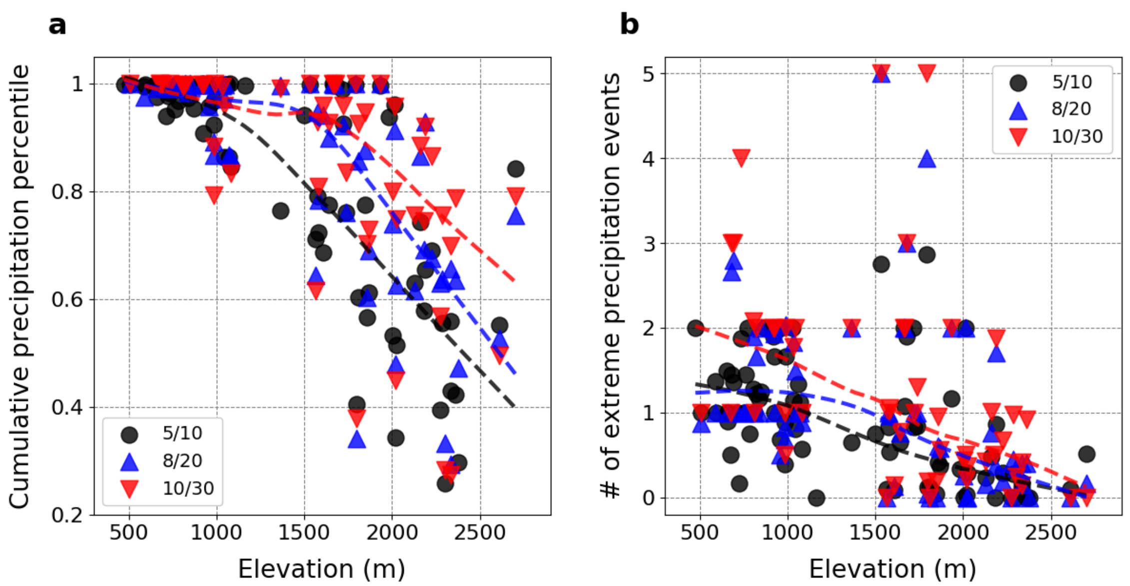

Figure 10. (a) Average cumulative precipitation percentile during and 10 days prior to persistent flood events as a function of mean catchment elevation. Black circles (respectively blue triangles, red triangles) correspond to events characterized by at least 5 (respectively 8, 10) days within a 10-day (respectively 10-day, 20-day) window with discharge above its 99$^{\mathrm{th}}$ percentile.

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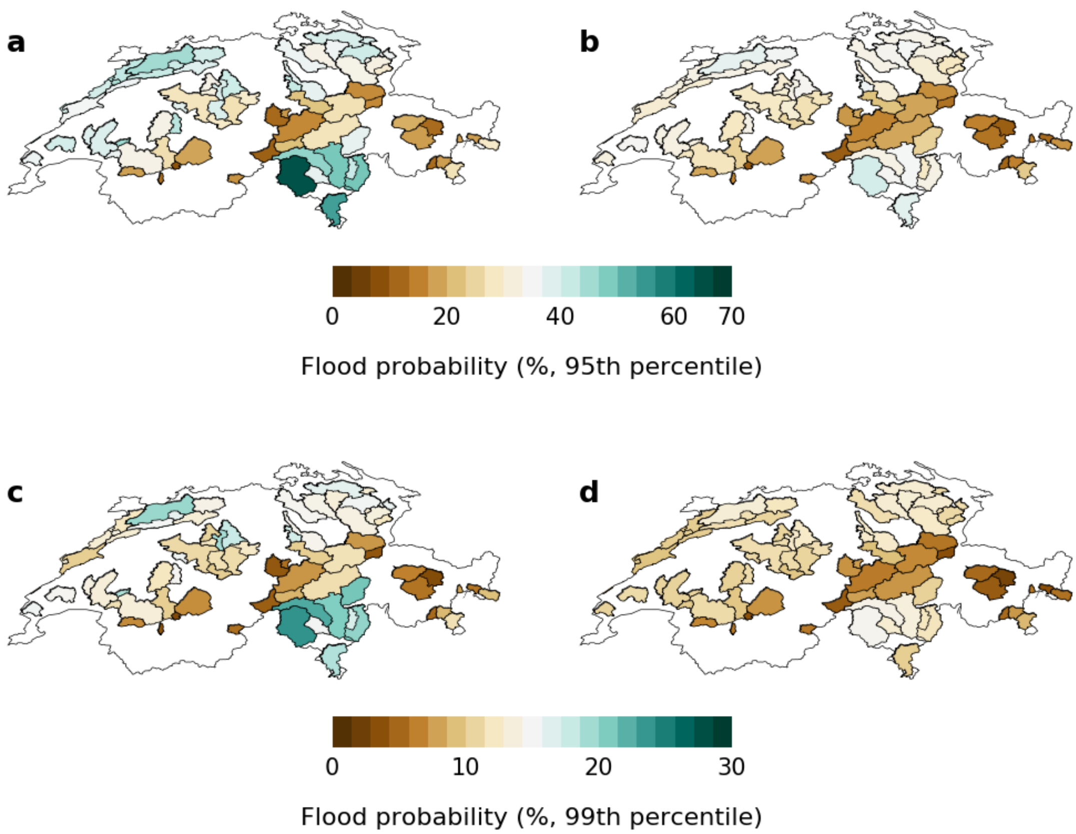

Figure 11. (a,b) Fraction of days with discharge above its 95^{th} percentile in the 5 days following (a) an extreme precipitation event that is part of a 21-day cluster and (b) any random precipitation extreme. (c,d) Same as (a,b) but for the 99^{th} daily discharge percentile.

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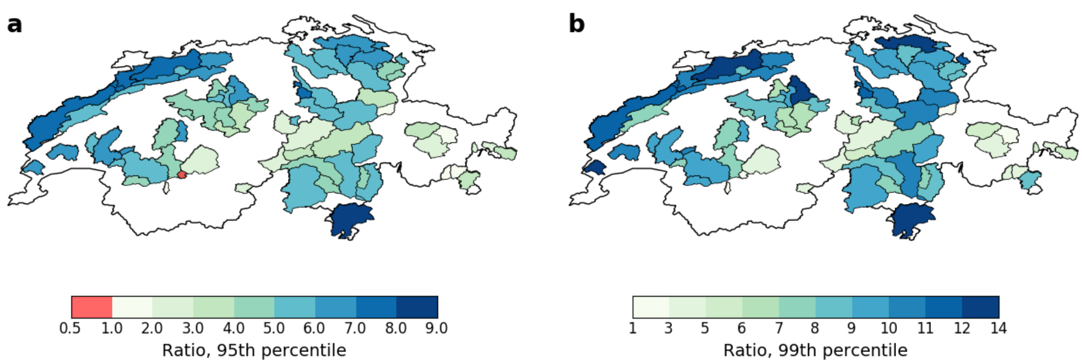

Figure 12. Ratio of the probability of flood days (defined based on daily (a) 95$^{\text{th}}$ and (b) 99$^{\text{th}}$ percentiles) during cluster events and up to 5 days after, to a reference flood day probability (see main text for the definition).

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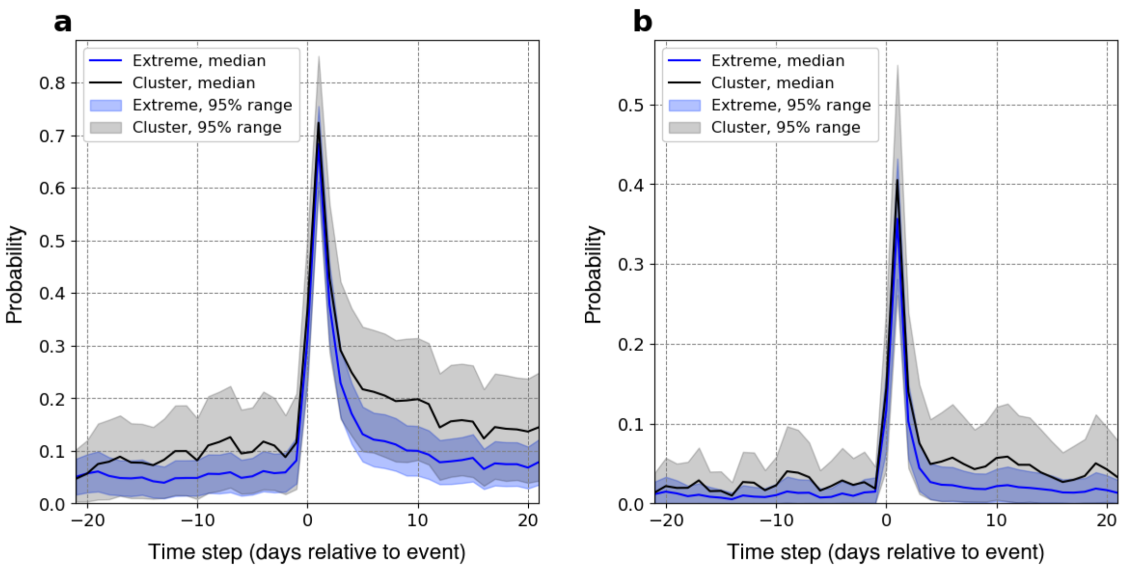

Figure 13. Probability of exceeding the (a) 95^{th} and (b) 99^{th} percentile of daily discharge around an extreme precipitation event that is part of a 21-day cluster (black) and around any random precipitation extreme (blue) across catchments with a mean elevation smaller than 1500m. Solid lines correspond to the multi-catchment median and shading to the 95% range.