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Seasonal characteristics of flood regimes across the Alpine–Carpathian range

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S U M M A R Y

The aim of this paper is to analyse the differences in the long-term regimes of extreme precipitation and floods across the Alpine–Carpathian range using seasonality indices and atmospheric circulation patterns to understand the main flood-producing processes. This is supported by cluster analyses to identify areas of similar flood processes, both in terms of precipitation forcing and catchment processes. The results allow to isolate regions of similar flood generation processes including southerly versus westerly circulation patterns, effects of soil moisture seasonality due to evaporation and effects of soil moisture seasonality due to snow melt. In many regions of the Alpine–Carpathian range, there is a distinct shift in flood generating processes with flood magnitude as evidenced by a shift from summer to autumn floods. It is argued that the synoptic approach proposed here is valuable in both flood analysis and flood estimation.

1. Introduction

The study of the seasonality of various hydrological processes and its spatial properties has recently attracted renewed interest, especially in connection with water resources management, flood and low flow regionalization, and land cover and climate change assessment studies (e.g. Majercáková et al., 1995; Lecce, 2000; Krasovskaia and Gottschalk, 2002; Krasovskaia et al., 2003; Bower et al., 2004; Garcia and Mechoso, 2005; Laaha and Blöschl, 2006a; Holko et al., 2006; Chalušová et al., 2006; Sauquet et al., 2008; Beurton and Thieken, 2009).

Beside the evergreen interest in comparative hydrology (Falkenmark and Chapman, 1989; Blöschl, 2006), regional flood frequency analysis can be regarded as one of the driving forces for this development. In this field typically studies were conduced where homogeneous regions with respect to the flood regime were defined as geographically contiguous regions, geographically non-contiguous regions, or as hydrological neighbourhoods (Ouarda et al., 2001; Merz and Blöschl, 2005). These were mostly delineated according to similarity measures based on catchment physiographic and climatic characteristics (see e.g. Wiltshire, 1985; Acreman and Sinclair, 1986; Blöschl et al., 1999; Castellarin et al., 2001; Pfaundler, 2001; Claps and Laio, 2004; Solin, 2008; Merz and Blöschl, 2005; Kohnová et al., 2006; Gaál et al., 2008). In recent years, similarity measures based on flood seasonality have become increasingly popular in identifying hydrologically homogeneous regions and pooling groups (e.g. Burn, 1997; Merz et al., 1999; Lecce, 2000; Piock-Elena et al., 2000; Castellarin et al., 2001; Cunderlik and Burn, 2002a,b; Ouarda et al., 2001, 2006; Cunderlik et al., 2004a,b; Laaha and Blöschl, 2006b). The robustness of the flood date data sets is an advantage of this approach since they are practically error-free (Ouarda et al., 2006). Since mechanism generating floods usually depends on the season, the seasonality approach opens the way to studying mixed flood frequency distributions in flood frequency analysis using the information on the seasonality (Ouarda et al., 2006; Sivapalan et al., 2005).

In addition to time of the year, the weather circulation patterns associated with floods have been used to identify the processes during floods (e.g. Webb and Betancourt, 1992; Fasko and Lapin, 1996; Kästner, 1997; Jain and Lall, 2000; Bárdossy and Filiz,

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2005; Steinbrich et al., 2005; Jucundus et al., 2006; Kyselý and Huth, 2006; Zehe et al., 2006; Petrow et al., 2007, 2009). Most of these studies have focused on finding flood triggering circulation patterns to assist in regional flood analyses.

The above studies provided valuable insight into the regimes of extreme events, but most of them only analysed a single country or region. However, much is to be learned from an analysis of larger regions. The main advantage is that, in a large region, most of the physiographic variability lies within that region, so the spatial analysis is less constrained by the boundaries in space. The regional scale perspective is also very important for relating the floods to atmospheric circulation processes, as the weather patterns go across the country boundaries.

The aim of this paper is to analyse the flood regimes across the Alpine–Carpathian range which covers a large part of Europe. The main idea is to understand the differences in the long-term regimes of extreme precipitation and floods across the range using seasonality indices and atmospheric circulation patterns to capture the main flood-producing processes. This is supported by cluster analyses to identify areas of similar flood processes, both in terms of precipitation forcing and catchment processes. The cluster analysis also assists in linking the seasonality and circulation patterns to shed light on the relationship between precipitations and flood regimes.

This paper goes beyond the existing literature in that a combined approach is used for the seasonality assessment over a large region. Besides using standard indices, the seasonality assessment is based on the evaluation of three largest annual maxima of extreme flood and precipitation events. This allows us to relate the flood regime to the most extreme events. This study aims to be the first assessment of flood regimes crossing the borders of France, Italy, Switzerland, Germany, Austria, Slovakia, Hungary, Ukraine and Romania along the Alpine–Carpathian range. The seasonality of floods and extreme precipitation is visualized by maps to obtain an appreciation of the spatial and temporal variability.

The paper is organised as follows. First we describe the methods used in the seasonality assessment and the hydrological data available for the analysis. The results section compares the seasonality of annual maxima of precipitation and runoff, examines their magnitude and spatial variability using different seasonality indices, and shows the results of the cluster analysis and the relationship to circulation patterns. Finally, we discuss the spatio-temporal variability in the hydrological regimes and present some concluding remarks.

2. Methods

2.1. Seasonality analysis

The seasonality analysis of maximum daily annual floods and precipitation is based on directional statistics (Mardia, 1972) which represent an effective method for defining similarity measures on the basis of the timing of hydrological extreme events with a year. Bayliss and Jones (1993) and later Burn (1997) introduced indices which reflect the mean date and variability of occurrence of extreme events. The date of occurrence D of an event in year i can be plotted on a unit circle to give the angle Θ_i in polar coordinates:

$$\Theta_i = D2\pi/365, \tag{1}$$

where $D = 1$ stands for January 1 and $D = 365$ for December 31. The direction $\overline{\Theta}$ of the average vector from the origin represents the mean date of occurrence of all annual events in a catchment or at a station. The $\bar{x}$- and $\bar{y}$-coordinates of the mean date are obtained from the sample of n extreme events by:

$$\bar{x} = \sum_{i=1}^{n} \cos(\Theta_i)/n, \tag{2}$$

$$\bar{y} = \sum_{i=1}^{n} \sin(\Theta_i)/n, \tag{3}$$

$$\overline{\Theta} = \tan^{-1}(\bar{y}/\bar{x}). \tag{4}$$

The variability of the date of occurrence about the mean date is characterized by the length parameter r:

$$r = \sqrt{\bar{x}^2 + \bar{y}^2}/n \tag{5}$$

which ranges from $r = 0$ (uniform distribution around the year) to $r = 1$ (all extreme events at a station occur on the same day). In order to investigate the change of the seasonality with the magnitude of extreme events, the seasonality indices (r and $\overline{\Theta}$) for a given station were separately estimated from all data and three largest annual maximum values (Sivapalan et al., 2005). In the following, the seasonality indices of daily annual maximum precipitation and floods are denoted as $\overline{\Theta}_P$, r_P and $\overline{\Theta}_F$, r_F, respectively.

2.2. Cluster analysis

Identification of groups of catchments with similar annual flood and precipitation regimes was based on the k-mean clustering technique (IMSL, 1997). The groups were obtained by minimising the sum of squares of the differences between the variables $z_{i,j,m}$ and the corresponding cluster centroid $\bar{z}_{j,m}$:

$$\phi = \sum_{i=1}^{K} \sum_{j=1}^{v} \sum_{m=1}^{n_i} w_j (z_{i,j,m} - \bar{z}_{j,m})^2, \tag{6}$$

where K is the number of clusters, v is the number of variables (see Table 1), n_i is the number of catchments in cluster i and w_j is the weight of variable j (Table 1).

For grouping the flood regime, the following eight variables j were used: the mean date of occurrence of annual floods represented by the cosine and sinus functions: $\cos(\overline{\Theta}_F)$ and $\sin(\overline{\Theta}_F)$; the variability of the mean date of flood occurrence r_F, the mean date of occurrence of the annual precipitation maxima represented by the cosine and sinus functions: $\cos(\overline{\Theta}_P)$ and $\sin(\overline{\Theta}_P)$; the variability of the mean date of occurrence r_P and the spatial proximity of the catchments defined by the X_{cor} and Y_{cor} planar coordinates of the runoff gauges. The precipitation stations were associated with the stream gauges closest to them. The basin boundaries were not available for the analyses, so distance was simply measured by the Euclidean distance between the stations and gauges. In order to minimize the effects of different magnitude and scaling of the selected variables, all variables were normalized by z-score transformation in advance of clustering. The weights w_j of the variables were estimated in test simulations (not shown here and partly discussed in Piock-Elena et al., 2000) and represent the relative

Table 1
Weights (w_j) of the variables j in the k-mean clustering.

Variable j	Weight w_j
$\mathrm{Cos}(\overline{\Theta}_F)$	0.6
$\mathrm{Sin}(\overline{\Theta}_F)$	0.6
r_F	0.1
$\mathrm{Cos}(\overline{\Theta}_F)$	0.4
$\mathrm{Sin}(\overline{\Theta}_F)$	0.4
r_P	0.1
X_{cor}	0.2
Y_{cor}	0.4

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importance of the variables subjectively given when delineating similar flood regimes. The largest weights were given to the flood seasonality. Less weight was given the X_{cor} distance than to the Y_{cor} distance because of the West East extension of the Alps. The final weights applied in this study are given in Table 1.

The validation and estimation of the final number of clusters was based on the Silhouette validation (Rousseeuw, 1987). The silhouette value S_i for each catchment characteristics in a cluster (S_i) is a measure of how similar that catchment is to catchments in its own cluster compared to catchments in other clusters. The S_i is defined as:

$$S_i = \frac{(b_i - a_i)}{\max\{a_i, b_i\}}, \tag{7}$$

where a_i is the average distance from the ith point to the other points in its cluster, and b_i is the average distance from the ith point to points in another cluster. The S_i range varies between -1 and +1. The case $S_i = 1$ means a well-clustered sample, the case $S_i = 0$ means that the sample could be well assigned to the closest cluster and the case $S_i = -1$ means that the sample is misclassified. For the estimation of the final number of clusters, the overall S_i average was calculated. The largest S_i average value (S_{avg}) determines the most representative number of clusters.

3. Data

The seasonality of flood regime is evaluated over the Alpine–Carpathian range. The region includes the South-Eastern part of France, Switzerland, the northern part of Italy, Austria, the southern part of Germany, Slovakia, Romania and a small region along the Ukraine–Hungarian border (Fig. 1). The region represents diverse climatologic conditions between the Atlantic, the Mediterranean and the continental part of Europe. The precipitation regime is influenced by western Atlantic airflows, meridional circulation patterns from the South and the continental climate in the East.

This study is based on data collected in the HYDRATE project (Gaume et al., 2009). The data include the time series of annual maximum runoff and annual maximum daily precipitation at stations with at least 20 years of measurements in the period 1961–2000. The annual maxima represent the observed daily maximum in each calendar year. The precipitation dataset consists of 1945 stations, the annual maximum flood data of 577 stream gauges. The size of the catchments is less than 500 km^2, with an exception of 16 catchments in Germany, which range between 750 and 2600 km^2. More details on the date are given in Table 2. The spatial distribution of the stations and the topography of the study region are presented in Fig. 1. The top and bottom panels show the location of the precipitation and runoff gauges, respectively. The density of stations varies across the study region. Detailed observations were available for Switzerland, Austria and northern Italy, but a smaller number of stations was available in France and the eastern part of the Carpathians in Ukraine. For the visualization of the results a 20 km grid representing the median values in each

Table 2
Number of stations used for the seasonality assessment in different countries. The first value represents the number of stations, the second the median of the record length (years) in the period 1961–2000. All stations have more than 20 years of observations and catchment size is less than 500 km^2.

Country	Extreme precipitation	Extreme floods
Austria	520/37	190/40
France	47/40	22/33
Germany	169/40	16[a]/40
Hungary	17/40	16/35
Italy	582/30	14/23
Romania	82/40	126/38
Slovakia	56/40	62/38
Switzerland	461/38	128/36
Ukraine	11/40	3/39

[a] Catchments in Germany are larger than 500 km^2.

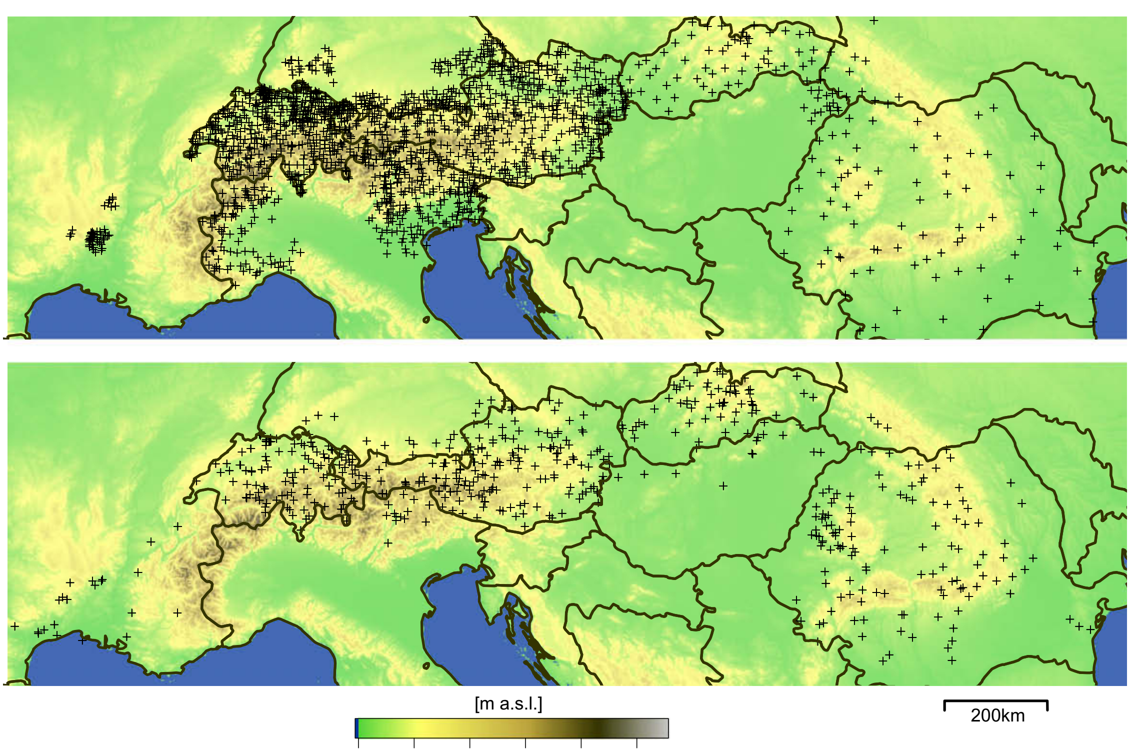

Fig. 1. Topography along the chain of Alps and Carpathians and the location of precipitation stations (top) and streamflow gauges (bottom).

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was applied. Fig. 2 shows the density of stations in each grid, indicating that a 20 km grid resolution is a reasonable compromise between the level of generalization and visualization performance.

3.1. Catalogue of weather circulation patterns

For the description of typical large-scale circulation weather patterns that may induce extreme precipitation and flood events, the Hess and Brezowsky Grosswetterlagen (GWL) classification system was applied. The GWL scheme is based on a subjective classification of daily circulation patterns over Europe in the period 1881–2004 (Gestengabe and Werner, 2005). The mapping concept is based on the characterization of the main flow direction of air masses; distinguishing zonal, meridional and mixed weather regimes. The original GWL classification divides the large-scale circulation patterns into 29 weather types. Gestengabe and Werner (2005) summarized these types into six groups (see Table 3), which are, for the purpose of this study, used for the description of the general weather regime during extreme precipitation and flood events. More information and general characteristics of particular GWL weather types (with the abbreviations used in Table 3) are provided by Gestengabe and Werner (2005) and James (2007) among others.

The monthly frequencies of the GWL groups are presented in Fig. 3. The frequencies express the relative occurrence (in%) of a particular GWL group in each month during the period 1961–2000. Fig. 3 shows that the Zonal West and the Mixed weather regimes dominate, while the Mixed CE weather type is very rare. The meridional circulation patterns occur more frequently in summer than in the winter months.

The relationships between the occurrence of annual maxima of precipitation, floods and typical weather circulation pattern are analysed by evaluating the relative frequency of weather types on the day of the annual precipitation maxima, and the day and two preceding days of the annual floods.

Table 3
Groups of typical circulation weather patterns based on the Grosswetterlagen catalogue (GWL).

GWL group	GWL type (Gestengabe and Werner, 2005)
1. Zonal West	WA, WZ, WS, WW
2. Mixed	SWA, SWZ, NWA, NWZ, HM, BM
3. Mixed Central Europe (CE)	TM
4. Meridional North (N)	NA, NZ, HNA, HNZ, HB, TRM
5. Meridional Northeast and East (NE, E)	NEA, NEZ, HFA, HFZ, HNFA, HNFZ
6. Meridional Southeast and South (SE, E)	SEA, SEZ, SA, SZ, TB, TRW

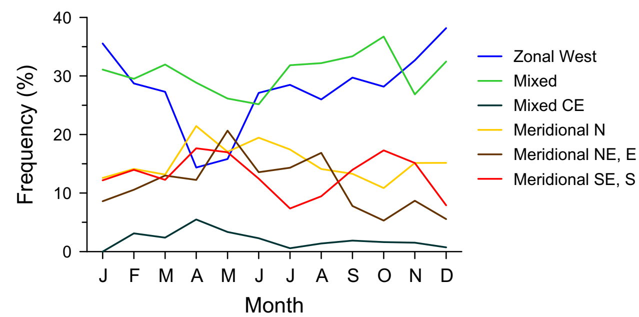

Fig. 3. Frequency of occurrence of different circulation patterns classified in the Großwetterlagen catalogue in the period 1961–2000.

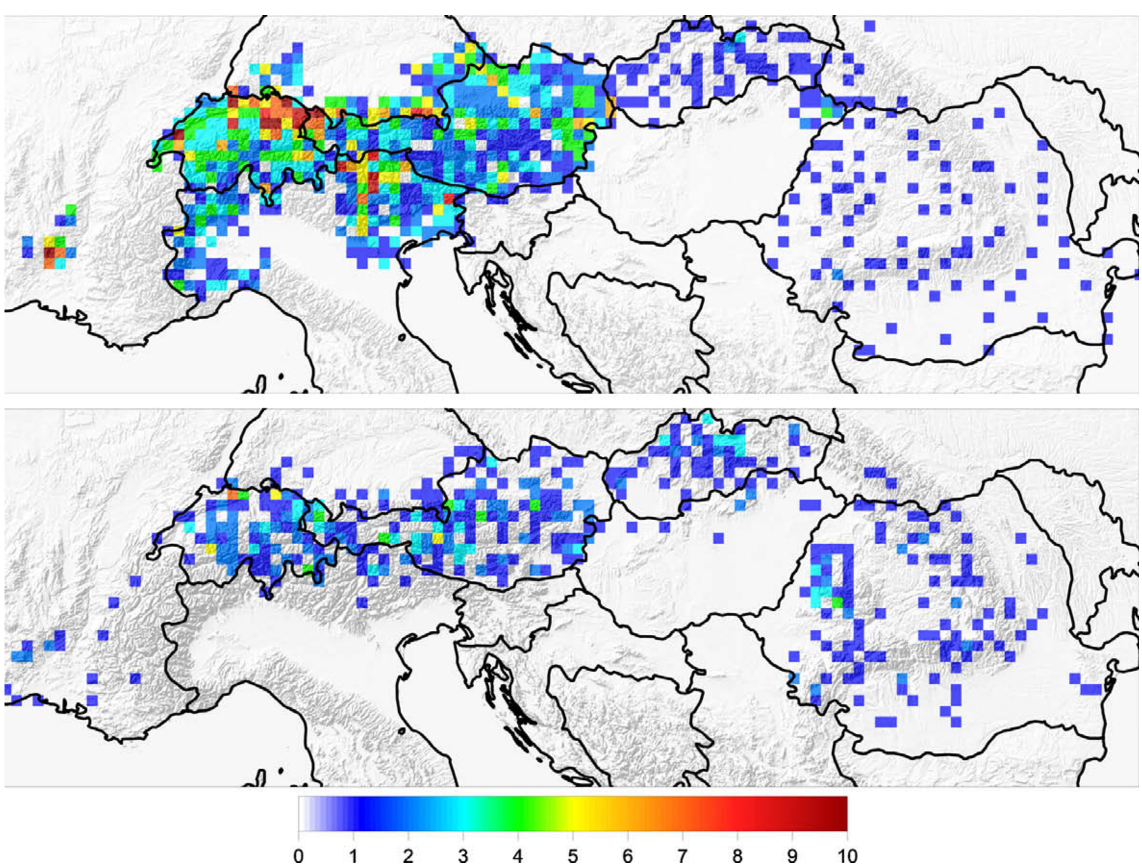

Fig. 2. Number of stations per 20 × 20 km grid cell. Precipitation stations (top) and streamflow gauges (bottom).

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4. Results

4.1. Seasonality of extreme precipitation

The spatial patterns of the mean date and variability of occurrence of the annual maximum daily precipitation over the Alpine–Carpathian range are presented in Fig. 4. The top panel shows the month of the mean date $\overline{\Theta}_P$ of the extreme events estimated from the complete dataset (1961–2000). In the Carpathian Arch and the northern part of the Alps the annual precipitation maxima typically occur in July and August. A shift of the maxima to the late summer and autumn is observed in southern Austria, South Tirol, Graubünden and Tessin in the South-Eastern part of Switzerland. In the southern part of Switzerland (Wallis region), there is a noticeable change in the timing of the occurrence of precipitation maxima, where extreme daily precipitation occurs in spring. The influence of Mediterranean circulation causes a distinct regional pattern in the seasonality over the Cevennes–Vivarais region in France and the north-eastern part of Italy. In these regions, the most extreme storm events are induced by instabilities produced by the confrontation between the cold air masses brought from the North and the warm Mediterranean Sea, which result in typical autumn precipitation maxima.

The variability in the mean date of occurrence is presented in the bottom panel of Fig. 4. Much lower seasonality is observed over the Alps than over the Carpathians. In Slovakia and Romania, rainfall occurrence is quite consistent with r_P varying mostly between 0.5 and 0.7. The very low seasonality over the central Alps in Austria is likely caused by orographic rainfall which may occur throughout the year. Similarly, the meridional circulation induces heavy convective storms throughout the year over northern Italy, which results in large variability and thus little seasonality of extreme precipitation.

The seasonality of the three largest precipitation maxima is presented in Fig. 5. The top panel shows similar patterns of the seasonality as those estimated from all observations in the period 1961–2000. Some difference occur in north-western Italy (Piedmonte) and the central Alps in Switzerland, indicating that the largest precipitation events tend to occur more than 2 months later than the average of all events. The seasonality of the largest events (Fig. 5, bottom panel) is much larger than that of all events. This suggests that the largest events are consistently produced by similar atmospheric regimes, while a wider variety of processes is responsible for the smaller events.

4.2. Seasonality of extreme runoff

The seasonality of maximum annual floods is presented in Figs. 6 and 7. Generally, the patterns show very heterogeneous seasonality of the flood occurrence along the Alpine–Carpathian range, which is due to differences in climate and catchment processes and, in particular, altitude. In the highest Alpine–Carpathian catchments floods tend to have a strong seasonality ($r > 0.8$) in June and July. In these regions, snow and glacier melt are important flood-producing processes together with heat advection and rain. As precipitation mostly falls as snow in winter, winter floods are very rare. The seasonality in lower catchments in the entire region is not very strong and has similar tendency of the mean occurrence of floods in March and April. In southern Austria and southern Switzerland floods tend to occur in late summer. In these regions the seasonality of extreme precipitation indicates that the influence of weather patterns from the south is the main causing factor of floods.

The seasonality of the three largest flood events (Fig. 7) indicates that the largest shift in the mean time of flood occurrence is observed in the mountainous parts of central Slovakia, central

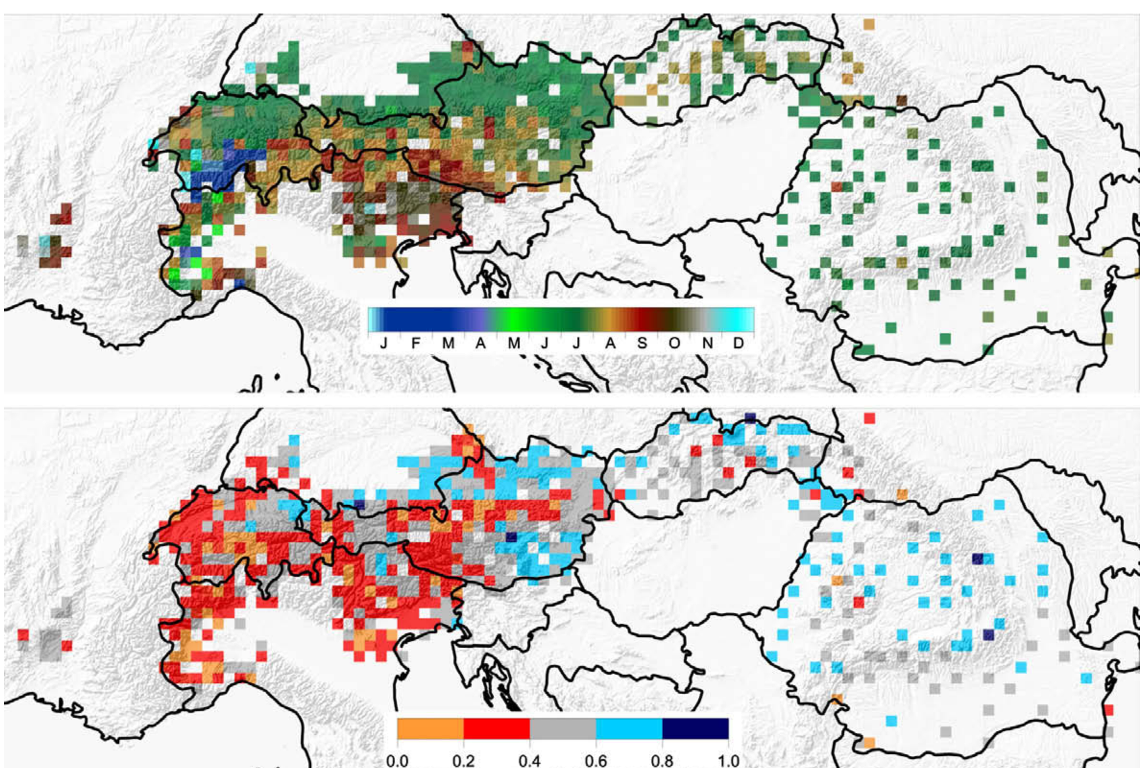

Fig. 4. Seasonality of annual maximum daily precipitation in the period 1961–2000, showing the mean date $\overline{\Theta}_P$ (top panel) and variability of occurrence r_P (bottom panel) of all observed extreme precipitation events ($r_P = 0$ indicates uniform occurrence throughout the year, $r_P = 1$ indicates that all maxima occur on the same day of the year).

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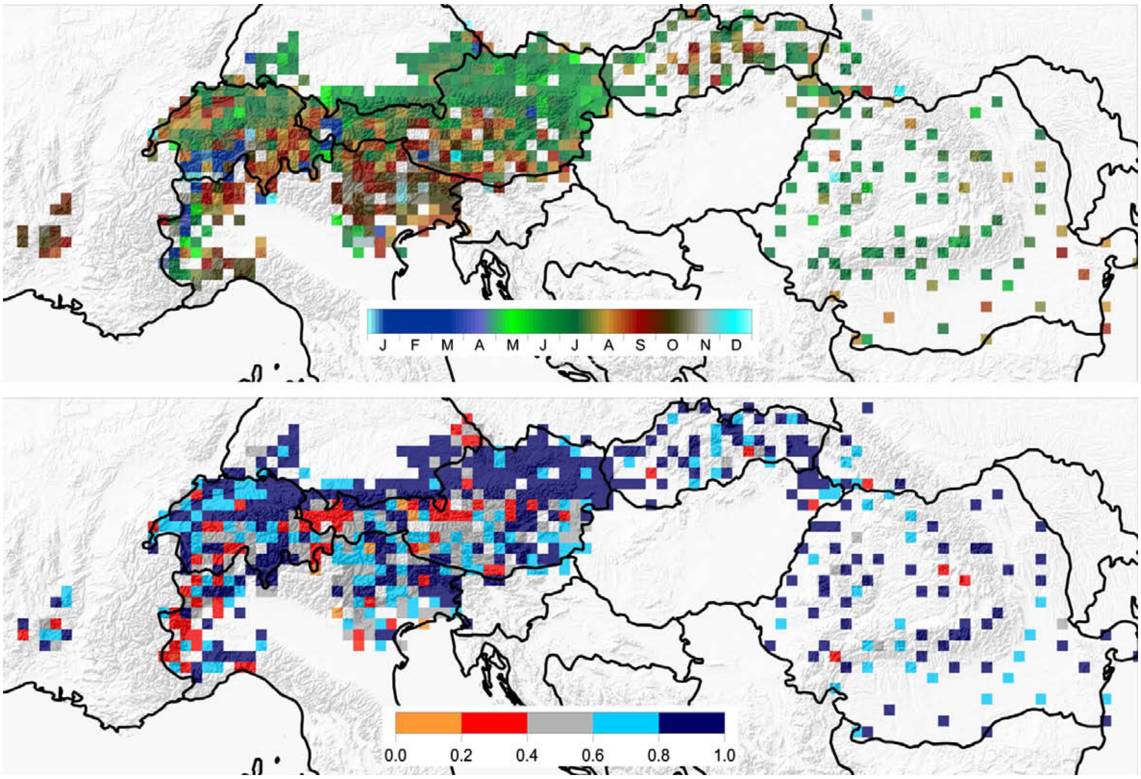

Fig. 5. Seasonality of annual maximum daily precipitation in the period 1961–2000, showing the mean date $\overline{\Theta}_P$ (top panel) and variability of occurrence r_P (bottom panel) of the three largest extreme precipitation events.

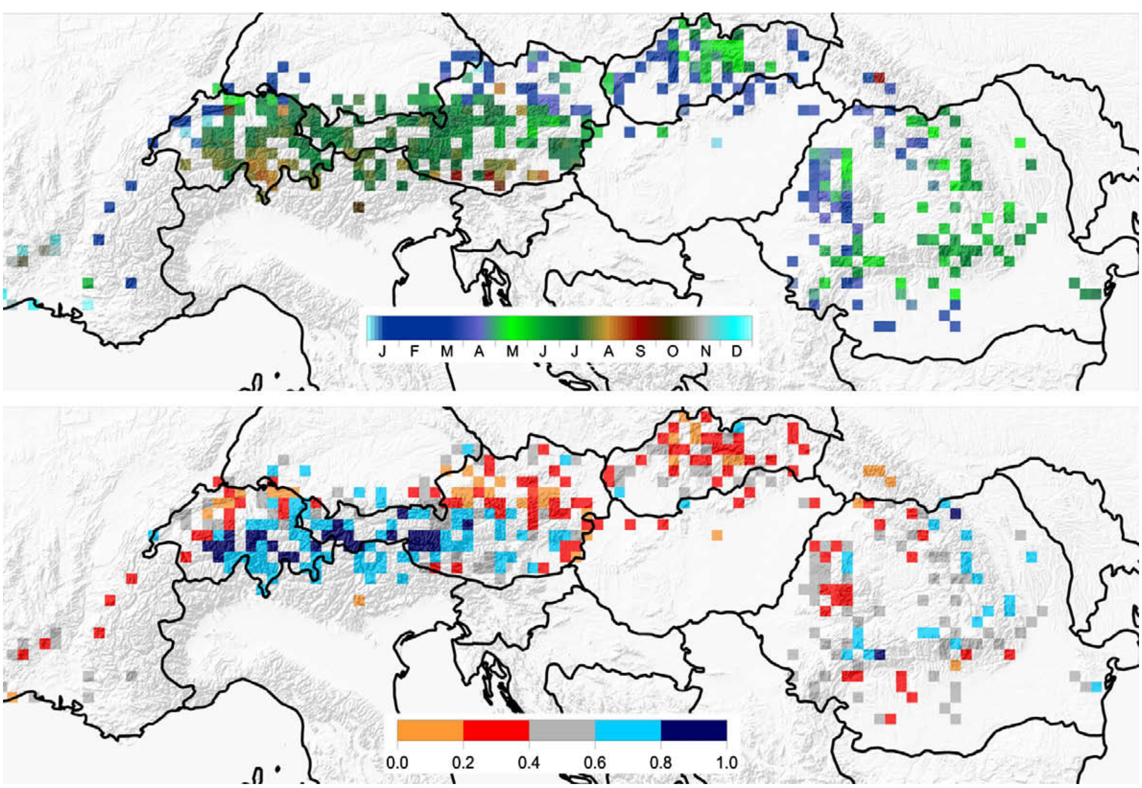

Fig. 6. Seasonality of annual maximum floods in the period 1961–2000, showing the mean date $\overline{\Theta}$ (top panel) and variability of occurrence r (bottom panel) of all observed extreme flood events.

Austria and the southern part of Romania. In these regions, the three largest floods occur in the late summer, more than 2 months later than the average of all annual floods. This is because the largest floods are mainly due to spring time rainfall while smaller floods can be produced by a variety of processes including snow melt, rain on snow, and convective storms. An opposite shift is observed for the Cevennes catchments, where the largest floods occur in early winter, approximately 1 month earlier than the average

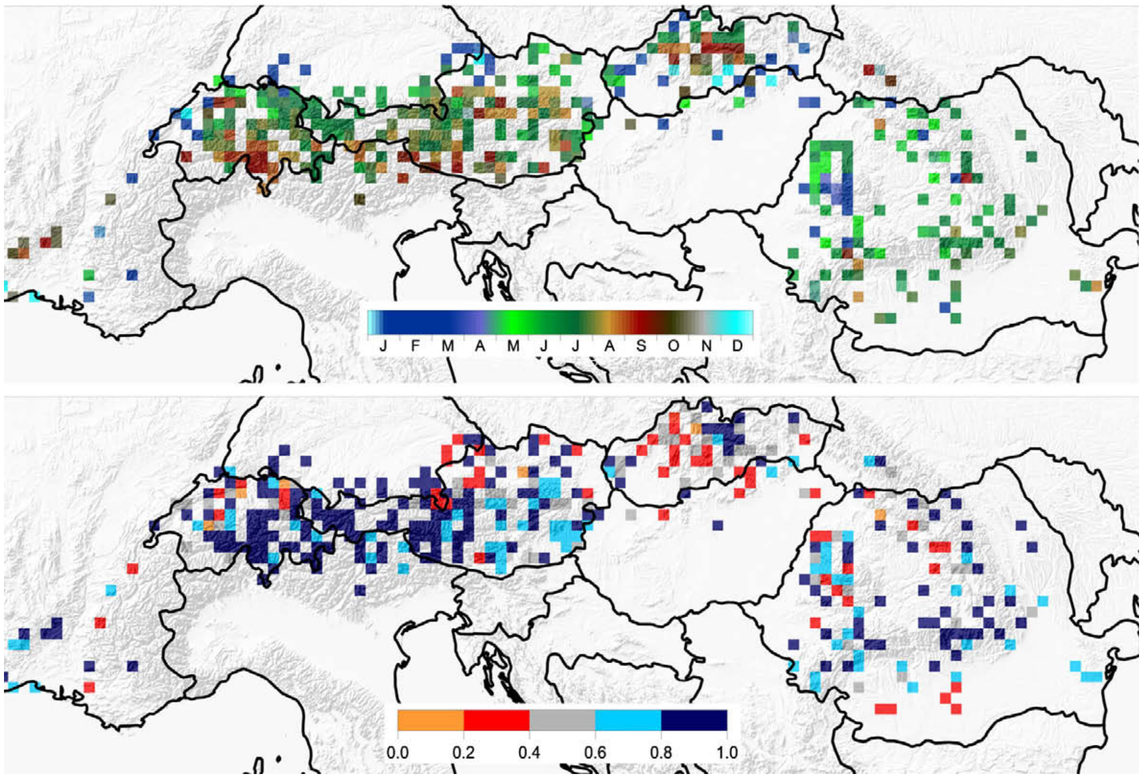

Fig. 7. Seasonality of annual maximum floods in the period 1961–2000, showing the mean date (top panel) and variability of occurrence *r* (bottom panel) of the three largest flood events.

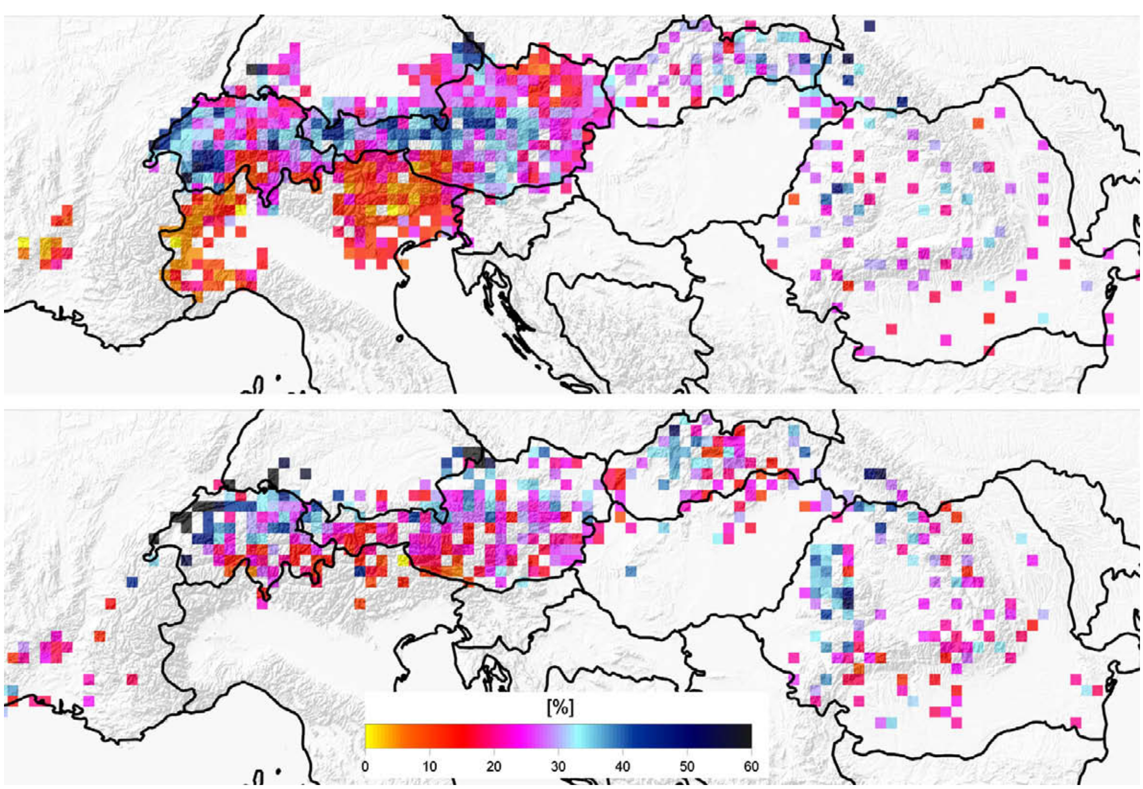

Fig. 8. Relative frequency of annual maximum precipitation (top panel) and floods (bottom panel) that have occurred during the Zonal West weather circulation situation in the period 1961–2000.

ones. This is in line with the seasonality of the largest precipitation events in the late autumn, which has an impact on the soil moisture state of the catchments. Interestingly, the largest floods in some catchments of central Slovakia and southern Romania have very weak seasonality. This corresponds likely to the seasonal variability of the precipitation maxima and a complexity of the flood formation factors (snowmelt, convective and stratiform precipitation types) in this region (Parajka et al., 2009).

4.3. Links between annual maximum floods and circulation weather patterns

The effect of weather patterns on extreme rainfall and floods is demonstrated here in terms of the frequency of the weather patterns during the events (Figs. 8 and 9). These figures represent the two most distinct regional patterns of the frequency of the Zonal West and the Meridional South and South-East circulation types. The Zonal West circulation induces more than 50% of the annual precipitation maxima along the main Alpine ridge in Austria, central Alps and Jura region in Switzerland and few stations in southern Germany and the Ukraine. In contrast, in northern part of Italy and the Cevennes, the Zonal West synoptic situation rarely results in annual precipitation maxima. In the Carpathian region, the annual precipitation maxima caused by the Zonal West circulation occur in 20–35% of the cases, with the exception of the Bihor Mountains (Romania), where more than 40% of the occurrences are observed at a few stations. The spatial pattern of the frequency of the Zonal West circulation floods is similar to that of precipitation. This consistency lends additional credence to the interpretation of flood generating processes in the context of circulation patterns. An exception is in central Austria, where the maxima occur less frequent than precipitation extremes. Here snow processes contribute to flooding, which result in a less tight relationship between precipitation and floods for a given circulation pattern.

Table 4
Results of the Silhouette validation for the estimation of final number of clusters. The largest S_{avg} indicate the most effective clusters.

Number of clusters	Silhouette average S_{avg}
5	0.379
6	0.460
7	0.468
8	0.475
9	0.403
10	0.425
11	0.472
12	0.440
13	0.447
14	0.443
15	0.437

The frequency of the Meridional South-East and South weather regime gives quite different spatial patterns. These synoptic situations rarely result in extreme precipitation or flood events in the Carpathians and northern part of the Alps. In the southern part of the Alps, however, this situation dominates in the frequency of extreme events. More than 60% of the annual precipitation maxima have occurred during the Meridional South and South-East weather types in the Cevennes, Piedmont, Aosta and South Tirol. Again, the spatial pattern of the frequency of floods is similar, with the exception of the Cevennes region, where annual floods may occur during several different circulation patterns.

4.4. Clustering the seasonality of annual maximum precipitation and floods

It is now interesting to examine how these seasonality characteristics analysed above can be used to identify regions that are similar in terms of their flood regime. To find a suitable number

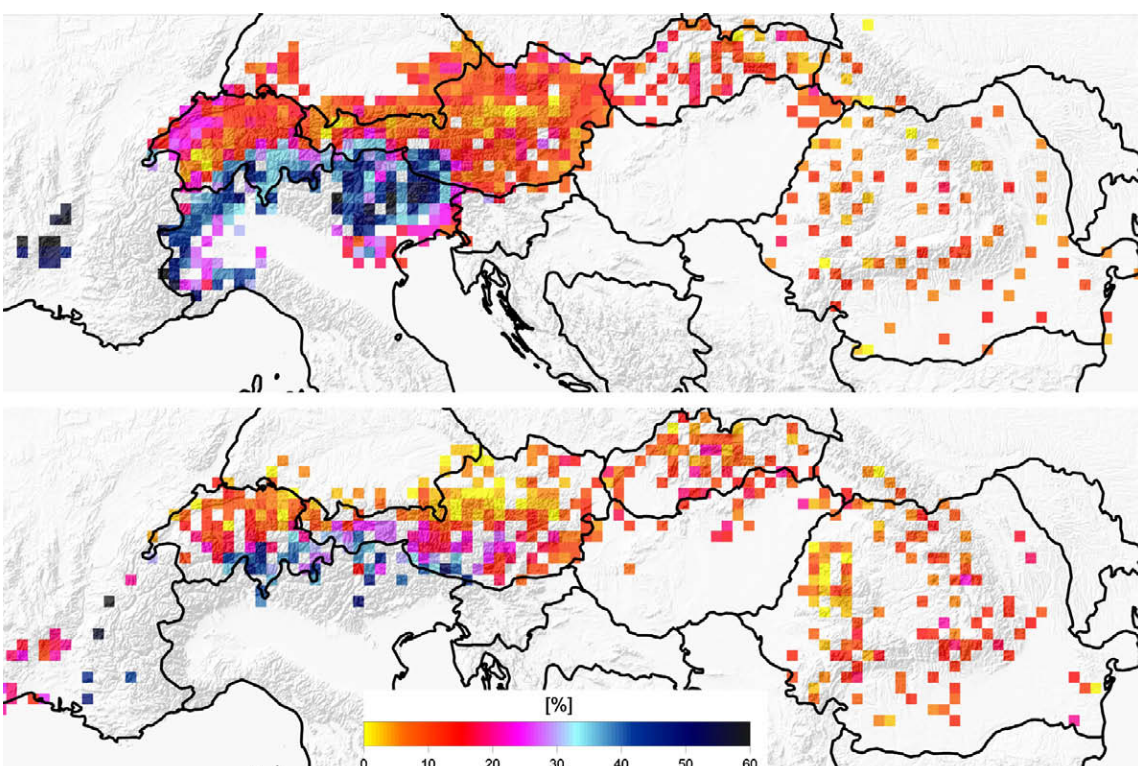

Fig. 9. Relative frequency of annual maximum precipitation (top panel) and floods (bottom panel) that have occurred during the Meridional South-East and South weather circulation situation in the period 1961–2000.

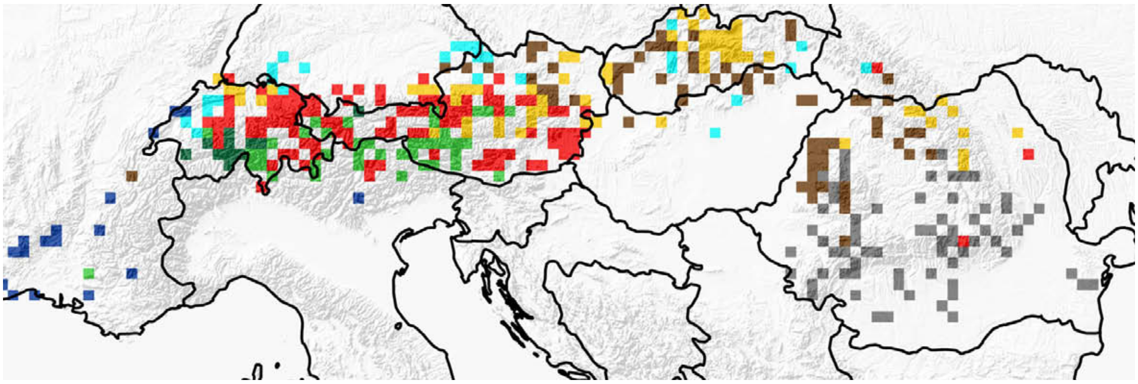

Fig. 10. Spatial arrangement of catchments with similar seasonality of annual flood and precipitation maxima. Seasonality of each group is presented in Fig. 11.

of clusters, the Silhouette average volumes (S_{avg}) were calculated for a number of clusters ranging from 5 to 15. The comparison of S_{avg} values (Table 4) indicates that the best clustering is represented by eight clusters, although the differences to other numbers of clusters (e.g. 11) are not large. Fig. 10 identifies the spatial location of the eight clusters. Fig. 11 compares the season (month) of the mean dates of precipitation and flood maxima. Overall, in some groups, the date of extreme precipitation and floods coincide while, in other groups, this is not the case. The differences are mainly due to soil moisture and snow processes. Specifically, in all clusters summer rainfall prevails with the exception of clusters 3 and 6 where southerly airflows are dominant. In all clusters catchment processes modulate the timing of flooding either through soil moisture or snow melt or both. The exception is cluster 1 where both extreme rainfall and floods occur in summer.

The dominant flood inducing weather types and dominant season of flood occurrence for each cluster group are evaluated in Fig. 12. From the assessment, it is clear that the floods tend to occur during different weather situations in each group. The most distinct influence occurs in Group 4, where more than 50% of the floods were caused by the Zonal West circulation pattern. The Meridional S and SE circulation types are important flood generation mechanism in catchments identified in cluster Groups 3, 5 and 6. The dominance and importance of seasons is especially clear in the catchments identified in cluster Groups 1, 5 and 6. In these catchments, the summer (July–August) floods dominate. In contrast, in the catchments of Groups 3 and 4, winter floods tend to dominate.

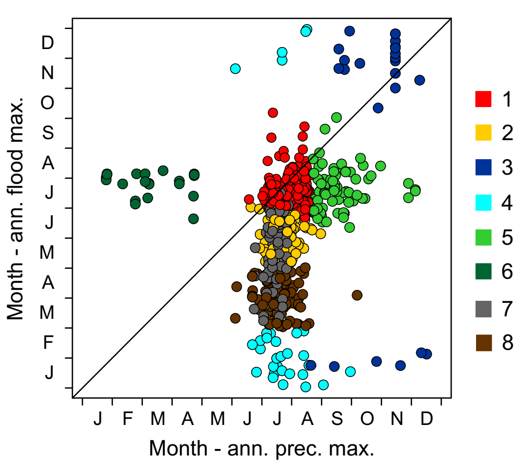

Fig. 11. Seasonalities of annual maximum precipitation and floods along the Alpine–Carpathian range. The eight groups of similar flood regimes relate to Figs. 10 and 12.

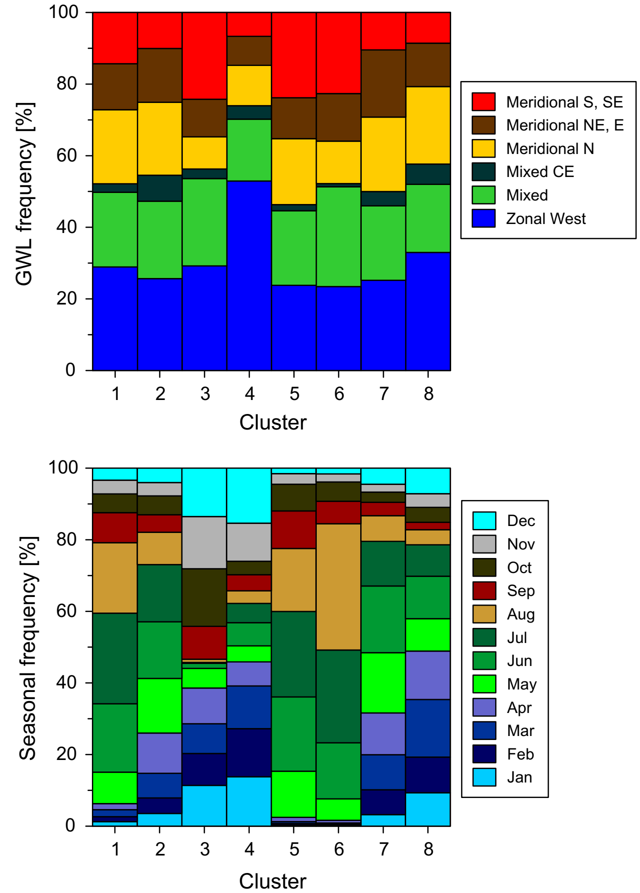

Fig. 12. The dominant flood inducing weather circulation patterns (top panel) and the dominant seasons of flood occurrence (bottom panel) for each cluster group. The relative frequency of the weather circulation patterns (GWL) is estimated from the day and the two preceding days of the maximum annual floods.

5. Discussion and conclusions

The cluster analysis along with the results of the circulation patterns allow us to focus on the differences between rainfall and flood seasonality to shed light on the nature of precipitation forcing and catchment processes in terms of the flood generating mechanisms. Table 5 gives a summary of the process interpretations based on the seasonality of annual maximum daily precipitation and annual maximum floods in the eight clusters of Figs. 10 and 11. Precipitation processes are reasoned in terms of the timing

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Table 5
Seasonality of annual maximum daily precipitation and annual maximum floods in the eight clusters of Figs. 10 and 11, from West to East. Precipitation processes are reasoned in terms of the timing and circulation patterns (Figs. 8, 9 and 12); flood processes are reasoned in terms of the differences in the timing relative to precipitation as well as in the changes as one moves from average to large events (Figs. 6 and 7).

Group (colour in Figs. 10 and 11)	Location (mean elevation of stream gauges)	Precipitation	Floods
Group 3 (dark blue)	Cevennes and surroundings (530 m a.s.l.)	September–December; flood producing storms due to southern air flows (Merid S, SE) (Fig. 12)	October–February; delay of floods due to wetter soils in winter than in autumn. Large floods tend to occur exactly in October–November due to extreme storms when soil moisture is less relevant (Fig. 7)
Group 4 (light blue)	Prealpine, low areas of Southern Germany, Slovakia (470 m a.s.l.)	July–August; flood producing storms due to westerly air flows (Zonal West)	December–February; wet soils in winter mainly due to snow and frozen soils, hence typical rain-on snow floods (Christmas floods). Floods may occur throughout year (Fig. 6)
Group 6 (dark green)	Southern high Alpine Switzerland, Wallis (1400 m a.s.l.)	February and April; but weak seasonality (Fig. 4); flood producing storms due to southern air flows (Merid S, SE) and Zonal West (Fig. 8)	July; floods due to less extreme storms, sometimes with snow and glacier melt. No winter floods due to high altitudes.
Group 5 (light green)	Highest parts of SE Switzerland, Southern Austria, Northern Italy (1200 m a.s.l.)	Late August–November; flood producing storms due to southern air flows (Merid S, SE)	June–August; earlier floods than extreme precipitation due to soil moisture increase of late spring snow melt. Extreme floods a little later until October (Fig. 7)
Group 1 (red)	Eastern Switzerland, northern lower Alpine region in Austria, SE Austria (860 m a.s.l.)	July–August; neither southerly nor westerly air flows dominant	July–August; minor influence of late spring snow melt on soil moisture due to lower elevations than Group 5. The western part of this group is a high rainfall regions where soil moisture tends to be high throughout the year, the eastern part of the group convective summer storms may be important
Group 2 (yellow)	Central parts of Austria and Slovakia, north-eastern Carpathians in Romania (570 m a.s.l.)	July–August; neither southerly nor westerly air flows dominant	May–June; lower elevations than Group 1, so snowmelt effects on soil moisture are earlier and hence earlier floods. Extreme floods a little later until October, in particular in central Slovakia (Fig. 7).
Group 8 (brown)	North-eastern part of the Carpathian Basin, and hilly and lowland regions of Austria and Slovakia (330 m a.s.l.)	July–August; no dominant circulation patterns, with a tendency for Zonal West (Fig. 8), strong seasonality of extreme rainfall in summer (Fig. 5)	March–May; pronounced shift in seasonality and processes with increasing event magnitude. Small floods in March (effect of snow melt on antecedent soil moisture), large floods in June and July (extreme rainfall) (Fig. 7)
Group 7 (grey)	Southern Carpathians, Bihor Mountains and hilly regions of western Transylvania in Romania (450 m a.s.l.)	July–August; no dominant circulation patterns	March–June; occasional extreme floods a little later until Sep. (Fig. 7). Timing is similar to that of Groups 2 and 8 combined but slightly stronger seasonality due to higher elevations

and circulation patterns (Figs. 8, 9 and 12). Flood processes are reasoned in terms of the differences in the timing relative to precipitation as well as the changes as one moves from average to large events (Figs. 6 and 7). Table 5 gives the driving processes in the clusters from West to East.

Catchments in Group 3, typically, have storms in late autumn where warm and moist air is advected from the Mediterranean Sea, and a time delay in flooding due to high soil moisture states in winter. Similarly, in Group 4 soil moisture is the main driver in modulating the timing of flooding. However, in this case it is mainly related to snow processes. In Group 4 these winter rain-on snow events are typical of southern Germany and other low land regions and have been termed Christmas floods (Merz and Blöschl, 2003; Sui and Koehler, 2001; Beurton and Thieken, 2009). Group 6 only covers a small, high alpine area in southern Switzerland, where snow and glacier melt are important. In Group 5 snow effects on soil moisture also exist, but there is a stronger influence of southern air masses than in Group 6. Group 1 contains catchments with still lower elevations, so the soil moisture effects are a little earlier in the season, and Group 2 catchment are still in somewhat lower elevations. Floods in Group 8 are related to either snow melt effects on antecedent soil moisture or long duration rainfalls. Group 7, finally, has a stronger seasonality in flooding than the regions 2 and 8 which is mainly due to the higher elevations.

It is interesting, that in many of the groups, there is a distinct shift in flood generating processes with flood magnitude as evidenced by the shift in flood seasonality. Often, extreme floods tend to occur in autumn while smaller floods may occur in summer (Groups 3, 5, 2, 7, see Table 5). This is an important finding as it may assist in extrapolating floods from smaller observed events to larger events that may not yet have occurred in a particular catchment. In these groups, small and moderate flooding in summer is related to the frequent storms in summer. However, there may be quite unusual and extreme events in autumn that are related to southerly circulation patterns when warm and moist air is advected from the Mediterranean Sea. Figs. 4–7 also indicate a general shift in the degree of seasonality as one moves from small and moderate events to the extreme events. The extreme events are more likely to occur in one particular season. The marked seasonality of extreme flood events has also been observed by Gaume et al. (2009), who studied a reduced set of the largest floods observed on gauged and ungauged rivers in the same region. This suggests that, while small events can be produced by a range of mechanisms (including short and long storms, effects of snow melt on antecedent soil moisture, rain on snow, various atmospheric circulation patterns), extreme events are often produced by one main mechanism. In many parts of the Alpine–Carpathian range this mechanism consists of extreme storms during southerly circulation patterns. Several extreme flood events of the recent two decades (in 1997, 2002 and 2005) were the consequence of meridional and blocking types of patterns along the northern slopes of the Alps and in the Carpathians. Interestingly, Bárdossy and Filiz (2005) explain certain tendencies to more frequent flood patterns in the northern Alpine region by the increased frequency of meridional circulation types.

The analysis also illustrates the dominant effect of soil moisture on modulating the rainfall regime to produce the flood regime. Depending on the area within the Alpine–Carpathian range, the seasonal soil moisture changes may be mainly due to the seasonality in evaporation (with low soil moisture in summer and high soil moisture in winter) or snow melt effects on increasing soil moisture. This is in line with the monthly regime classification of Pardé (1955), who reported a higher stability of the flow regimes with glacial/snow melting as the main flow generating process and instability of the regimes in the rain-fed rivers. It appears that the main effect of snow melt, in most cases, is not the direct input of the melt water to a flood event but the indirect effect of increasing antecedent soil moisture. This is consistent with the analyses of Sivapalan et al. (2005) and Parajka et al. (2009) on the regimes of mean monthly precipitation and runoff who emphasised the role of the water balance in flood generation. There are interesting interactions across time scales as the water balance affects flooding both directly through event precipitation, as well as indirectly through modulating antecedent moisture. Also, there is a very clear elevational effect in most clusters on the flood timing and hence flood processes. As the catchments increase in elevation, the snow melt effects on soil moisture move from winter to spring and summer.

As a final note, we think that this type of synoptic approach is valuable in both flood analysis and flood estimation. The cornerstone is to analyse a number of pieces of evidence at the same time, such as the timing of precipitation and flooding in a catchment, and atmospheric circulation patterns. By combining these pieces of information, a better understanding of the flood generation processes can be achieved than by traditional flood frequency analysis alone. Merz and Blöschl (2008a,b) have proposed the paradigm of "flood frequency hydrology" where the focus is shifted away from purely statistical analyses of flood peaks to a combination of process analyses with the traditional flood statistics. Their focus was on individual catchments, while this paper has demonstrated the viability of the flood frequency hydrology concept in a regional context within the Alpine–Carpathian range.

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