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A regional analysis of event runoff coefficients with respect to climate and catchment characteristics in Austria

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[1] In this paper we analyze the controls on the spatiotemporal variability of event runoff coefficients. A total of about 64,000 events in 459 Austrian catchments ranging from 5 to 10000 km^2 are analyzed. Event runoff coefficients vary in space, depending on the long-term controls such as climate and catchment formation. Event runoff coefficients also vary in time, depending on event characteristics such as antecedent soil moisture and event rainfall depth. Both types of controls are analyzed separately in the paper. The spatial variability is analyzed in terms of a correlation analysis of the statistical moments of the runoff coefficients and catchment attributes. Mean runoff coefficients are most strongly correlated to indicators representing climate such as mean annual precipitation and the long-term ratio of actual evaporation to precipitation through affecting long-term soil moisture. Land use, soil types, and geology do not seem to exert a major control on runoff coefficients of the catchments under study. The temporal variability is analyzed by comparing the deviation of the event runoff coefficients from their mean depending on event characteristics. The analysis indicates that antecedent soil moisture conditions control runoff coefficients to a higher degree than does event rainfall. The analysis also indicates that soil moisture derived from soil moisture accounting schemes has more predictive power for the temporal variability of runoff coefficients than antecedent rainfall.

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1. Introduction

[2] The event runoff coefficient, i.e., the portion of rainfall that becomes direct runoff during an event, is a key concept in engineering hydrology and is widely used for design and as a diagnostic variable to represent runoff generation in catchments. Event runoff coefficients can also be used in event-based derived flood frequency models [e.g., *Sivapalan et al.*, 2005] that estimate flood frequencies from rainfall frequencies and are useful for understanding the flood frequency controls in a particular hydrologic or climatic regime.

[3] Although the concept of event runoff coefficient dates back to the work of *Sherman* [1932], analyses of the controls of runoff formation are still an existing research issue in hydrology. Most of the studies have a focus on small areas, such as irrigation plots or hillslopes, summarized for example by *Anderson and Burt* [1990]. These studies point to a great variability in the factors controlling runoff formation during a rainfall event [*Weiler and McDonnell*, 2004]. For example, *Scherrer et al.* [2007] analyzed 48 high intensity sprinkling experiments on 18 mainly grassland hillslopes in Switzerland. They observed runoff rates varying from less than 2% to more than 90% of the rainfall rates. Which processes, e.g., Hortonian overland flow, saturation overland flow, fast subsurface flow and deep percolation occurred, depended on interactions between infiltration rate, change in soil water storage and drainage of the soil water. They found that the process occurrence is often not directly linked to parameters usually considered important, such as vegetation, slope, soil clay content and antecedent soil moisture, but considering the structure of the soil in combination with these attributes, process determination was often straightforward.

[4] On the catchment scale, the analysis of runoff formation during an event is mostly hampered by a lack of regional data of a large number of observed rainfall-runoff events covering a wide range of hydrological conditions that can occur in that region. Typically a moderate number of rainfall-runoff events in a few catchments in a region are analyzed. *Cerdan et al.* [2004], for example, analyzed 345 rainfall-runoff events in three catchments of different sizes in France to study scale effects in the runoff generation process. They found a significant decrease in the runoff coefficient as area increases. For catchments of the scale of 10 km^2 the percentage of arable land appeared to be a driving factor of runoff response. *Naef* [1993] analyzed the five to ten largest floods in about 100 Swiss catchments and concluded that the interactions of runoff coefficients and catchment conditions are very complex and hard to quantify, so runoff coefficients should hence be treated as random numbers. *Dos Reis Castro et al.* [1999] compared runoff coefficients at different scales, ranging from 1m^2 irrigation plots to two nested catchments (0.14–1 km^2) on a basaltic plateau in southern Brazil. *Gottschalk and Weingartner* [1998] examined runoff coefficients of 192 flood events in 17 Swiss catchments which they used in a derived flood

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frequency model. They fitted a Beta function to the distribution of runoff coefficients in each catchment and interpreted the parameters for different hydrologic regions in Switzerland. They concluded that the differences in runoff coefficients can be explained by topographic characteristics such as altitude and slope and to some degree by stream network density and geology.

[5] The U. S. Department of Agriculture's Soil Conservation Service (SCS) curve number method [*Soil Conservation Service*, 1972] can also be used to estimate event runoff coefficients in catchments. In the SCS curve number method event runoff coefficients are derived from a catchment's curve number, which is a function of land use and soil type and its adjustment according to antecedent rainfall to account for the variability in soil moisture conditions between events. In spite of its lasting popularity, the method is still a subject of debate, due to the criticism of the theory that underlies the method [e.g., *Michel et al.*, 2005] and its limited applicability across different climates and catchment types [e.g., *Kleeberg and Øverland*, 1989].

[6] A much larger data set of event runoff coefficients at the catchment scale was compiled by *Merz et al.* [2006]. They developed a methodology to estimate about 50000 event runoff coefficients in 337 Austrian catchments based on automatic base flow separation and event detection. They found regional patterns in the event runoff coefficients distribution, which they explained by the climate variability in Austria. However, they did not explicitly relate the runoff coefficients to event or physical catchment characteristics, so the process controls on the runoff coefficients at the catchments scale still awaits to be defined.

[7] The aim of this paper is to analyze the controls which contribute to the spatiotemporal variability of event runoff coefficients in Austrian catchments. It is a data based approach, which essentially is based on the data set of event runoff coefficients derived by *Merz et al.* [2006]. Specifically, we address the following research questions:

[8] 1. What are the dominant controls on the spatial variability of event runoff coefficients? Do runoff coefficients mainly vary between catchments due to different climate forcing or due the spatial variability in geology, soil types, land use or topographic characteristics of the catchment.

[9] 2. Is the temporal variability of runoff coefficients of the same catchment mainly controlled by the event rainfall conditions or by antecedent soil moisture conditions?

[10] These are the key questions to be addressed in order to develop appropriate methods for predicting runoff coefficients for ungauged catchments in an environment such as Austria.

2. Data and Methodology

2.1. Motivation and General Approach

[11] Event runoff coefficients vary in space and time, depending on the long-term controls and on event characteristics. Long-term controls such as climate or catchment formation do not vary at a short time scale and hence may contribute to the spatial variability of event runoff coefficients. Indicators to characterize the long-term controls are, e.g., mean annual precipitation and the percentage of area of a geological unit or soil type. These indicators may give a general trend of the event runoff coefficients. For example, in permeable catchments runoff coefficients tend to be lower than in impermeable catchments. The temporal variability of event runoff coefficients in a catchment can be related to the variability in event characteristics. The temporal variability depends on the catchment state prior to the event, which may be represented by antecedent rainfall. Runoff coefficients also depend on event characteristics such as event rainfall depth and the maximum intensity during an event.

[12] For a better understanding of the nature of runoff formation, it is advantageous to separate the two types of controls. In this paper, we assume that spatial variability is represented by the variability of the statistical moments of the observed runoff coefficient sample, i.e., mean runoff coefficients, standard deviation, coefficient of variation and skewness. The controls are analyzed in terms of the dependence of the statistical moments on catchment attributes, such as mean annual precipitation and soil types.

[13] The temporal variability is analyzed by the deviation from the mean runoff coefficients. With the focus on the temporal variability, the variability between events for many catchments are analyzed. The idea of two different controls of runoff coefficients is similar to the concept underlying the SCS curve number procedure [*Soil Conservation Service*, 1972], where the catchment's curve number represents the spatial variability of runoff coefficient and is derived from soil and land use data. For each event the curve number is then adjusted according to the antecedent rainfall to account for the temporal variability of runoff coefficients in one catchment.

2.2. Estimation of Event Runoff Coefficients

[14] In this study, event runoff coefficients for the period 1981–2000 are estimated from hourly catchment rainfall and discharge data from 459 Austrian catchments with catchment area ranging from 5 to 10000 km^2. Smaller catchments that were available in the region were discarded as the uncertainty introduced by the spatial rainfall interpolation was expected to be large. Larger catchments than 10000 km^2 were discarded as the within catchment variability of runoff coefficients was assumed to be large. All discharge data were carefully screened and only catchments without significant anthropogenic impacts were used [*Merz et al.*, 2006]. A total of 64461 events are analyzed in this paper. In the following section the method to derive event runoff coefficients from the hourly time series of rainfall and runoff is shortly described. For a more detailed description see *Merz et al.* [2006].

[15] In a first step, hourly catchment rainfall was estimated. To maximize rainfall information, hourly rainfall data from 143 recording stations (high temporal resolution) were combined with daily rainfall data from 1066 stations (high spatial resolution). Daily precipitation was disaggregated to hourly values using the approach of *Grebner* [1995] and *Grebner and Roesch* [1998] and then spatially interpolated using inverse distance weighting. The interpolated rainfall map for each hour was combined with the catchment boundaries to estimate hourly catchment precipitation. To examine possible biases of the method, hourly catchment rainfall was aggregated to annual values and compared with the mean annual rainfall of *Parajka et al.* [2005] who used external drift kriging with elevation to regionalise rainfall.

To account for elevation effects, catchment rainfall used in this study was increased by a factor that was allowed to vary with mean catchment elevation.

[16] Solid precipitation during an event will not directly contribute to event runoff but snowmelt from an existing snowpack will add to any liquid precipitation. To account for both effects, results from a daily water balance model [*Parajka et al.*, 2005] for each catchment have been used. The model is a semidistributed conceptual model and accounts for snow accumulation and snowmelt using threshold air temperatures and the degree day factor concept. The model was calibrated to daily discharges and snow cover data [*Parajka et al.*, 2005]. The daily model-simulated values were then disaggregated to hourly values. The ratio of liquid to solid precipitation was assumed constant for each day from which liquid hourly precipitation was estimated. For the temporal pattern of snowmelt during a day a truncated cosine distribution was assumed, where snowmelt started at 0900 LT, the maximum occurred at 1500 LT and snowmelt ceased at 2100 LT. The sum of liquid precipitation and snowmelt for each hour was used in the further analyses.

[17] The event runoff coefficient relates to direct runoff or quickflow only, so it was necessary to separate quickflow and base flow. In this study, an automatic method of base flow separation was used. A number of techniques proposed in the literature [*Grayson et al.*, 1996; *Tallaksen*, 1995] were tested for the data sets of this study and the digital filter proposed by *Chapman and Maxwell* [1996] yielded a base flow separation that most closely followed what one would separate manually by visual inspection. The *Chapman and Maxwell* [1996] filter was hence used here. The parameters of the filter were calibrated manually by visual inspection of the resulting separation of runoff data time series in each catchment.

[18] To separate rainfall-runoff events, it is necessary to identify the start and the end of an event. A procedure for event separation was developed on the basis of a set of criteria, to match the event separation one would do manually. Starting from the largest peak of each time series, the approach was repeated from larger events to smaller events. For each peak flow, the start of an event was searched within a given time period by finding the time where the direct runoff becomes lower than a given threshold, which depends on the direct runoff at the time of the peak flow. If no starting point was found, the search was repeated by gradually increasing the time period and the threshold. With this iterative approach, the direct runoff at the beginning of an event is as small as possible but if no such point in time is found, a higher direct runoff is allowed. The end of an event is found by a similar procedure. In case of overlapping events only the one with the larger peak flow was retained. The associated criteria were found by extensive tests and were examined for robustness. For all catchments the same set of criteria are used iteratively to separate all events. The method was thoroughly tested by visual inspection which indicated that it can indeed identify rainfall-runoff events for the runoff regimes of the study area in a similar way as manual separation.

[19] Event runoff coefficients are usually estimated as the ratio of event runoff volume and event rainfall volume. This is straightforward if all events are clearly separated and direct runoff between events is small. However, if the direct runoff at the end of an event is significantly larger than zero this ratio will underestimate the runoff coefficient as the trailing limb of the hydrograph is trimmed. To overcome this problem we fitted a simple event rainfall-runoff model to the direct hydrograph. In this runoff model, the runoff coefficient appears explicitly as a model parameter and can hence be estimated by optimising an objective function. This procedure is less sensitive to the choice of the start and end points of the events than the usual ratio of volumes. The model used is basically a linear reservoir model with storage parameter *kd* and a constant runoff coefficient rc. The two model parameter were calibrated minimizing the root mean square difference between the observed direct runoff hydrograph and the simulated direct runoff hydrograph using shuffled complex evolution optimization scheme of *Duan et al.* [1992]. For a small number of events the rainfall-runoff model could not be fitted satisfactorily to direct runoff from observed data and these were discarded.

[20] As the database of *Merz et al.* [2006] is extended by including more catchments, the database of this study consists of 64461 events in 459 Austrian catchments. From the rainfall-runoff simulations, event rainfall depth, duration and maximum intensity, antecedent rainfall soil moisture and snowmelt are derived for further analysis. The sample moments of the runoff coefficients were estimated for each catchment as

$$\text{mean} = \frac{1}{m}\sum_{j=1}^{m} \text{rc}_j, \tag{1a}$$

$$\text{Sdev}^2 = \frac{1}{m-1}\sum_{j=1}^{m}\left(\text{rc}_j - \text{mean}\right)^2, \tag{1b}$$

$$\text{CV} = \frac{\text{Sdev}}{\text{mean}}, \tag{1c}$$

$$\text{CS} = \frac{m\sum_{j=1}^{m}\left(\text{rc}_j - \text{mean}\right)^3}{(m-1)(m-2)\text{Sdev}^3}, \tag{1d}$$

where rc_j is event runoff coefficient of event j and m is the number of events observed in each catchment.

[21] In Figure 1 the standard deviation (Sdev), coefficient of variation (CV) and coefficient of skewness (CS) is plotted against mean event runoff coefficients. The pattern of Sdev reflects the upper and lower bound of the runoff coefficients. For catchments with small and high mean runoff coefficients (close to the lower and upper boundary), Sdev tends to be small, while the largest Sdevs are observed for catchments with mean runoff coefficients between 0.25 and 0.6. There is a clear trend of a decreasing CV and CS with increasing mean runoff coefficients. In catchments, where runoff coefficients tend to be large, the variability between the events is small compared to the mean value. In catchments where runoff coefficients tend to be small, events with high runoff coefficients can occur, if rarely,

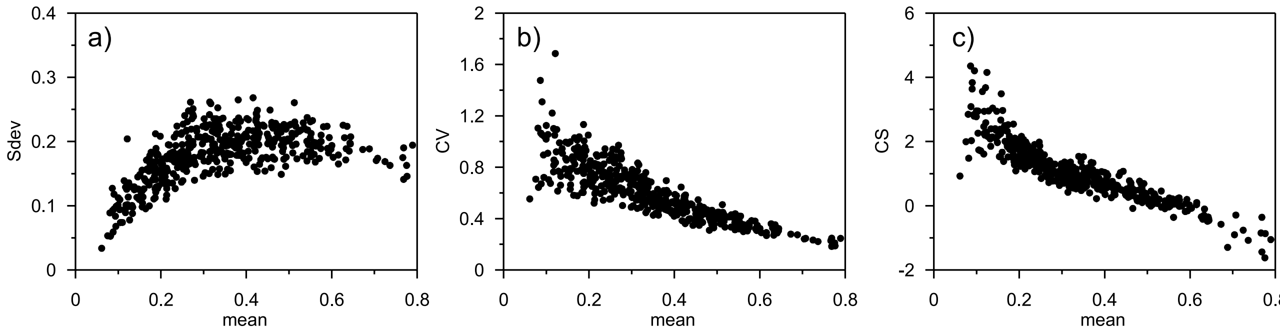

Figure 1. Statistical moments of the event runoff coefficients. (a) Standard deviation (Sdev), (b) coefficient of variation (CV), and (c) coefficient of skewness (CS) are plotted against mean event runoff coefficient. Each point represents a catchment.

which results in a much higher CV and CS. The Spearman's rank correlation coefficient between Sdev and the mean runoff coefficient is $r = 0.58$, that for CV and the mean runoff coefficient is $r = -0.82$ and that for CS and mean runoff coefficient $r = -0.87$.

2.3. Catchment Attributes

[22] A number of hydrologically relevant catchment attributes were used. Long-term actual evaporation (AET) and potential evaporation (PET) and their ratios to precipitation (AET/P and PET/P) were calculated by simulating the catchments daily water balance dynamics using a semi-distributed conceptual catchment model [*Parajka et al.*, 2005], following the structure of the HBV model [*Lindström et al.*, 1997]. The model simulates runoff routing on the hillslopes by an upper and a lower soil reservoir, representing fast (direct) runoff and base flow. A base flow index (BFI) is calculated as the ratio of runoff from the lower soil reservoir estimated by the catchment model and total runoff on a long-term scale. This definition differs from that what sometimes used in the literature and some of the BFI values are large. A BFI of one implies that all of the hillslope runoff is routed through the lower soil storage.

[23] Long-term mean annual precipitation (MAP) and information on daily precipitation were derived using over 1066 rainfall stations [*Parajka et al.*, 2005]. Topographic information was calculated from a digital elevation model of Austria [*Rieger*, 1999]. River network density was calculated from the digital river network map at the 1:50000 scale [*Fürst*, 2003] for each catchment. Information on hydrogeology [*Schubert*, 2003], land use [*Fürst and Hafner*, 2003], and soil types [*Österreichischen Bodenkundlichen Gesellschaft*, 2001] was also used.

[24] SCS curve numbers were estimated from soil and land use data. The digital soil map of Austria [*Österreichischen Bodenkundlichen Gesellschaft*, 2001] was used to identify approximate estimates of the soil group. Lithosols, rendzinas, podzols and histozols, i.e., high infiltration capacity soils, were classified as soil group A; fluvisols, phaeozems and chernosems as soil group B; cambisols as soil group C; and luviosols with a relatively low infiltration capacity as soil group D. Although it is clear that the type of soil information available at the regional scale will not provide any of the small-scale soil details found in catchments we do believe they represent the general regional patterns of soils characteristics to some extent. The digital map of land use [*Fürst and Hafner*, 2003] was used to assign land use or land cover. From both sources, the SCS curve numbers were inferred at a pixel scale of 250 m. These were averaged over each catchment area.

[25] The lengths of the main channel in each catchment were derived from the digital river network. The lengths were calculated beginning from the catchment outlet by following the stream upward. At a confluence, the main channel was assumed to be the stream that drains the largest catchment area. Catchment average values were then found by integration within each catchment boundary. The data sets used in the paper are summarized in Table 1.

2.4. Statistical Analysis of the Controls

[26] The controls on the spatial variability are analyzed by a correlation analysis of the first three moments (i.e., mean, coefficient of variation and skewness) of the runoff coefficient sample and catchment attributes. As the event runoff coefficients and the catchment attributes are not necessarily normally distributed, the Spearman rank correlation coefficient (r) was used here to measure the dependence of the event runoff coefficients on the catchment attributes

$$r = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \text{ with } d_i = rk(x_i) - rk(y_i), \quad (2)$$

where $rk(x_i)$ is the rank of x_i, where the highest value has rank 1 and the lowest value has rank n. Spearman's r varies between -1 and 1, where -1 represents a completely negative correlation and 1 represents a completely positive correlation. Completely uncorrelated pairs of data have a Spearman's r of 0.

[27] The controls on the temporal variability are analyzed by comparing the distribution of the relative deviation of the event runoff coefficient from their mean value, stratified according to event conditions such as catchment soil moisture state prior to the events and event rainfall depth. Two classes of conditions are analyzed: below average and above average. For example, events with event rainfall depth below and above average are separately analyzed.

2.5. Regions

[28] There is a large diversity of hydrological conditions in Austria, ranging from the lowlands in the east of the

Table 1. Indicators of Spatial Variability of Runoff Coefficients Used in the Project

Information	Abbreviation	Data
Climatic indicators	MAP	Long-term mean annual precipitation (mm/a)
	AET/P	Long-term ratio of actual evaporation to rainfall
	PET/P	Long-term ratio of potential evaporation to rainfall
	AET	Long-term actual evaporation (mm/a)
	PET	Long-term potential evaporation (mm/a)
Runoff ratio	BFI	Long-term ratio of base flow to runoff
Topography	Elevation	Mean catchment elevation (m asl)
	Slope	Mean topographic slope
	RND	River network density
	Channellength	Length of main channel/area (km/km^2)
	Centrelength	Length of main channel to center of gravity
	Channelslope	Averaged slope of main channel
Geology	Quat., limestone, clay, phylite, granite	Percentage of quaternary sediments; limestone, dolomite, and carbonate rock; clay, marl, and sandstone; phylite and schist; and granite and gneiss area in the catchment
Land use	Agricultural, forest	Percentage of agricultural and forest area in the catchment
Soils	Fluvisol, lithosol, rendzina, phaeozem, chernozem, cambisol, luvisol, podsol, histosol	Percentage of fluvisol, lithosol, rendzina, phaeozem, chernozem, cambisol, luvisol, podsol, and histosol area in the catchment
SCS curve number	SCS-CN	SCS curve number (depending on soil type and land use)

country, with mean catchment elevations of less than 200 m above sea level (asl), up to the high alpine catchments in the west of the country with mean catchment elevations of more than 2500 m asl. Mean annual precipitation ranges from less than 400 mm/a (where a is years) in the east to more than 3000 mm/a in the west, where orographic effects tend to enhance precipitation. Because of the large diversity of hydrological conditions, it is likely that also the process controls on the event runoff coefficients will differ across Austria. To better single out the controls on the event runoff coefficients, Austria was divided into five hydroclimatic regions. The regions have been delineated manually on the basis of an assessment of the hydroclimatic variability of Austrian catchments. The delineation of regions reflects the perception of the dominant meteorological and hydrological processes, as described below.

[29] In Figure 2 the locations of the hydroclimatic regions are shown. Each of the analyses in this paper is carried out for the whole area of Austria, as well as for five hydroclimatic regions separately. The ''alpine region'' covers the Alps in the west of Austria. Runoff generation in the catchments of this region is strongly affected by snow and glacier melt. Windward and leeward effects on northwesterly weather patterns are important. The ''southern alpine region'' covers the alpine catchments in east Tyrol and along the river Gail in the very south of Austria and the lower alpine region in the southeast of Austria. The hydrological conditions are similar to those of the alpine region,

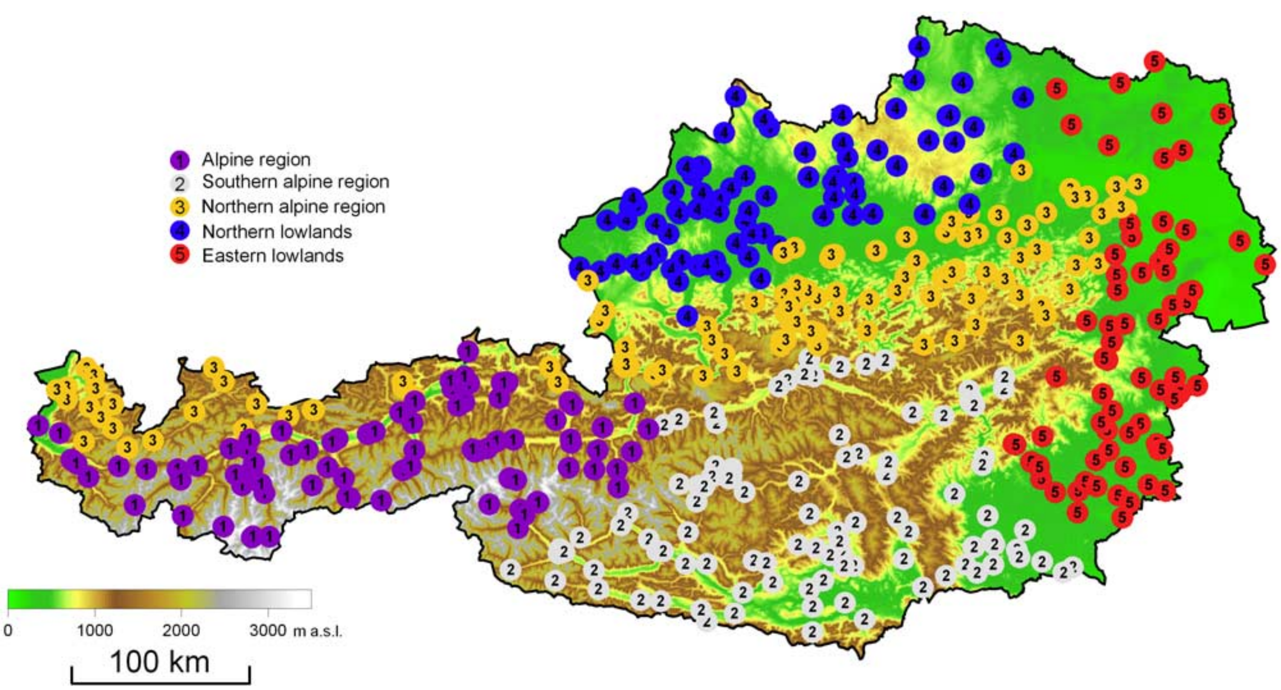

Figure 2. Location of hydrological regions in Austria. Numbers have been plotted at the location of each stream gauge [after *Merz and Blöschl*, 2008a].

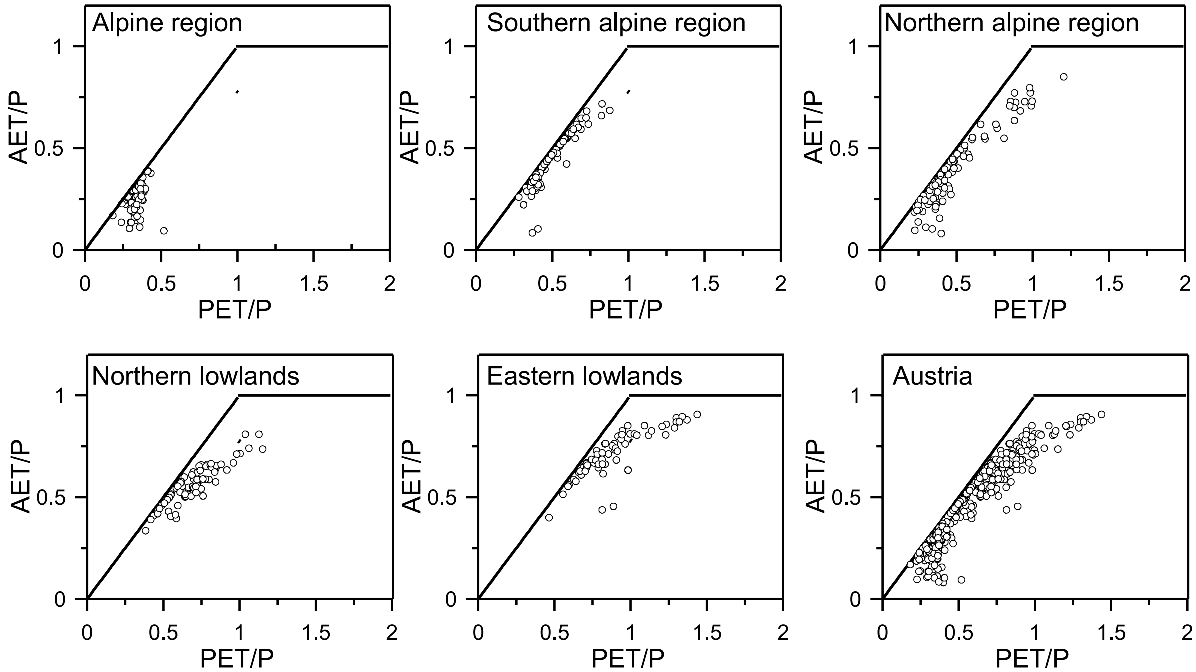

Figure 3. Budyko curves of Austrian catchments (after *Merz and Blöschl* [2008a]).

but storm tracks from the Mediterranean are important and hence strongly affect the soil moisture variability. In the lower part of the southern alpine region rainfall is significantly lower and snow processes are less important. The "northern alpine region" is on the northern fringe of the central Alps. This is the region of highest rainfall in Austria, because of the orographic barrier of the Alps to northwesterly airflows. The predominant geology is limestone and dolomite. The "northern lowlands" in the northwest of Austria are rather flat. Rainfall is lower than in the northern alpine region because of the smaller influence of orographic enhancement. The region "eastern lowlands" is the driest part of Austria and is located in the east and northeast. Most of the catchments are rather flat. Much of the geology is of tertiary and quaternary origin. The eastern part of the region is affected by the Pannonian climate, a continental climate with warm and dry summers, and cold winters without significant snowfall.

[30] The Budyko curves of the Austrian catchments classified by region are given in Figure 3. In terms of the Budyko curve, most of the Austrian catchments are classified as wet or humid catchments, as evaporation is mainly limited by energy. Only for some catchments in the eastern lowlands, evaporation is water limited and hence these catchments are classified as dry or arid catchments. Striking are the low rates of actual evaporation in some catchments in the alpine region. These are the high alpine catchments, where temperature is generally too low for higher evaporation rates. Some of these catchments are partly glaciated.

3. Results

3.1. Controls on the Spatial Variability

[31] The controls on the spatial variability are analyzed by a correlation analysis of the mean, standard deviation, coefficient of variation and skewness of the runoff coefficient sample of each catchment. The correlation of the moments to catchment attributes are given in Table 2.

[32] The first catchment attribute analyzed in more detail is long-term mean annual precipitation, which characterizes the hydroclimatic situation of a catchment. It is a surrogate measure of the average antecedent soil moisture state prior to a rainfall event and geomorphic catchment processes. In Figure 4 (top) mean runoff coefficients are plotted against MAP for each region, SDEV, CV, and CS are plotted against MAP for all of Austria in Figure 4 (bottom). There is a large variability in the runoff coefficients between and within the regions. In the dry eastern lowlands, where MAP is lower than 1000 mm/a, mean runoff coefficients of most catchments are lower than 0.25, while in the alpine region with MAP larger than 1000 mm/a, mean runoff coefficients are larger than 0.25. There is also a variability of mean runoff coefficients within the regions, e.g., in the northern alpine region mean runoff coefficients vary between 0.2 and 0.8.

[33] For all regions, except for the alpine region, mean runoff coefficients tend to increase with MAP. The correlation coefficient of mean runoff coefficients and MAP for all Austrian catchments is $r = 0.71$. For the alpine region $r = -0.38$, while for the remaining regions r varies between 0.42 and 0.68. Sdev tends to increase with increasing MAP and hence, CV is negatively correlated to MAP. For Austria, the correlation of CV and MAP is $r = -0.69$. Similarly to CV, CS is also negatively correlated to MAP with $r = -0.65$ for all Austrian catchments. The particular behavior of the correlation of the moments to MAP in the alpine region can be explained by the strong influence of snow and glacier melt on the catchments seasonal water balance. Removing all catchments which are partly glaciered the correlation coefficient of mean runoff coefficients and MAP increase to $r = 0.24$ and the correlation coefficients of CV and CS decrease.

Table 2. Correlation of Mean Annual Event Runoff Coefficients, Standard Deviation, Coefficient of Variation, Coefficient of Skewness, and Catchment Attributes[a]

	Austria				Alpine Region	Southern Alpine Region	Northern Alpine	Northern Lowlands Region	Eastern Lowlands Region
	Mean	Sdev	Mean	CS	Mean	Mean	Region Mean	Mean	Mean
Area	−0.01	−0.09	−0.03	0.11	−0.08	0.24	0.03	0.04	0.41
MAP	**0.71**	**0.35**	**−0.69**	**−0.65**	**−0.38**	**−0.42**	**0.69**	**0.50**	**0.46**
AET/P	**−0.81**	**−0.32**	**0.86**	**0.78**	**−0.62**	**−0.63**	**−0.83**	**−0.68**	**−0.61**
PET/P	**−0.70**	**−0.25**	**0.73**	**0.64**	**0.32**	**−0.53**	**−0.66**	**−0.53**	**−0.38**
AET	**−0.53**	**−0.09**	**0.53**	**0.46**	**−0.74**	**−0.61**	**−0.57**	**−0.01**	**−0.02**
PET	**−0.52**	**−0.09**	**0.60**	**0.42**	**−0.52**	**−0.46**	**−0.62**	**0.03**	**−0.31**
BFI	**−0.62**	**−0.36**	**0.53**	**0.62**	**−0.52**	**−0.61**	**−0.57**	**−0.42**	**−0.16**
Elevation	**0.60**	**0.11**	**−0.64**	**−0.46**	**0.48**	**0.57**	**0.62**	0.10	0.32
Slope	**0.67**	**0.19**	**−0.70**	**−0.56**	**0.25**	**0.70**	**0.59**	**0.38**	**0.49**
RND	**−0.29**	**0.13**	**0.37**	**0.20**	**−0.34**	**−0.49**	**−0.49**	**0.39**	0.17
Channellength	**−0.14**	**0.04**	**0.18**	0.06	−0.14	**−0.23**	−0.21	−0.14	−0.19
Centrelength	−0.09	0.01	0.06	0.06	−0.11	0.19	0.04	**−0.01**	**−0.12**
Channelslope	**0.39**	**0.10**	**−0.43**	**−0.36**	0.12	0.08	**0.25**	0.09	0.17
Quat.	**−0.24**	**−0.23**	**0.17**	**0.28**	**−0.51**	−0.01	−0.05	0.08	0.09
Limestone	**0.46**	**0.23**	**−0.43**	**−0.38**	**−0.27**	**0.34**	**0.41**	0.09	**0.47**
Clay	**−0.28**	−0.01	**0.36**	**0.20**	**−0.40**	**−0.03**	**−0.43**	**0.22**	**−0.14**
Phylite	0.02	**−0.13**	−0.07	**0.12**	**−0.42**	0.08	0.23	–	0.02
Granite	**−0.14**	**−0.19**	**0.09**	**0.21**	**0.54**	**−0.10**	**−0.02**	**−0.20**	**−0.27**
Agricultural	**−0.40**	**−0.14**	**0.41**	**0.35**	**−0.49**	**0.08**	**−0.15**	−0.06	**−0.29**
Forest	**−0.08**	0.06	**0.11**	**0.11**	**−0.47**	**−0.48**	**−0.08**	0.04	**0.27**
Fluvisol	0.02	0.00	−0.01	0.05	−0.04	0.20	−0.01	0.08	0.21
Lithosol	**0.60**	**0.11**	**−0.61**	**−0.48**	**0.26**	**0.74**	**0.48**	0.18	–
Rendzina	**0.39**	**0.24**	**−0.34**	**−0.34**	**−0.35**	**0.54**	**0.15**	**0.35**	**0.59**
Phaeozem	**−0.12**	**−0.09**	**0.14**	**0.19**	−0.13	–	–	–	−0.03
Chernozem	**−0.23**	**−0.17**	**0.23**	**0.24**	–	–	–	–	−0.27
Cambisol	**−0.62**	**−0.21**	**0.63**	**0.56**	**−0.47**	**−0.77**	**−0.40**	−0.01	**−0.30**
Luvisol	**−0.32**	**−0.18**	**0.30**	**0.31**	**−0.21**	**−0.11**	**−0.25**	−0.05	**−0.20**
Podsol	0.07	−0.01	**−0.11**	0.03	−0.12	−0.10	0.13	−0.22	–
Histosol	**0.10**	−0.03	**−0.12**	0.03	–	**0.29**	−0.09	−0.09	–
SCS-CN	**−0.25**	**−0.15**	**0.28**	**0.20**	**0.49**	**−0.31**	**−0.18**	0.06	−0.18

[a]Correlation coefficients that are significant at the 95% level are printed in bold.

[34] Other surrogate measures of antecedent soil moisture conditions used in this study are the long-term actual evaporation and potential evaporation and the long-term ratios of actual evaporation to rainfall and potential evaporation to rainfall. All indicators are negatively correlated to the mean runoff coefficients and positively correlated to CV and CS, except in the alpine region, where PET/P is positively correlated to the mean runoff coefficients. Similarly to MAP, the positive correlation of PET/P in the alpine region is a result of glaciered catchments. In Figure 5 mean runoff coefficients, Sdev, CV, and CS are plotted against AET/P.

[35] The results of the correlation analysis indicate that in wet catchments runoff coefficients tend to be high, which is what one would expect. The variability of runoff coefficients between single events is small in comparison to the mean runoff coefficients, which results in small CV and CS. In dry catchments runoff coefficients tend to be low, but a larger variability between the events occurs. This suggests that the hydroclimatic situation is one important control on the runoff coefficients. The climatic control on the runoff coefficients is found for the entire Austrian data set, as well as for each region individually.

[36] An index of the different runoff processes taking place in a catchment is the base flow index (BFI), calculated as the ratio of runoff from the lower soil reservoir estimated by the catchment model [*Parajka et al.*, 2005] and total runoff on a long-term scale. As direct runoff is assumed to be dominated by surface and/or near subsurface flow, one expects that the more water infiltrates to form subsurface flow (and hence increases the base flow index), the smaller event runoff coefficients are. This is corroborated by a negative correlation of mean runoff coefficients and base flow index with $r = -0.62$ for the entire Austrian data set (Table 2). CV is positively correlated with the base flow index for the entire Austrian data set with $r = 0.53$. In Figure 6 mean runoff coefficients, Sdev, CV, and CS are plotted against the base flow index.

[37] Other indicators often used to describe the hydrological condition in catchments are topographic indices, river network density, the SCS curve number and percent area covered by a geological unit, soil type or land use class. For the two topographic indices used in this study (mean catchment elevation and mean catchment slope) the correlations for the entire Austrian data set are rather high. In Figure 7 mean runoff coefficients, Sdev, CV, and CS are plotted against the mean elevation of catchments. Mean runoff coefficients tend to increase with catchment elevation, CV and CS tend to decrease with catchment elevation. This correlation deemed to be a result of a combination of several factors. First, rainfall tends to increase with elevation. MAP in the Austrian Alps is about 4 four times higher than in the lowlands of eastern Austria. Hence antecedent soil moisture tends to be higher in alpine catchments. Second, snow cover and glaciers increase runoff coefficients. Third, high alpine catchments tend to have a shallow

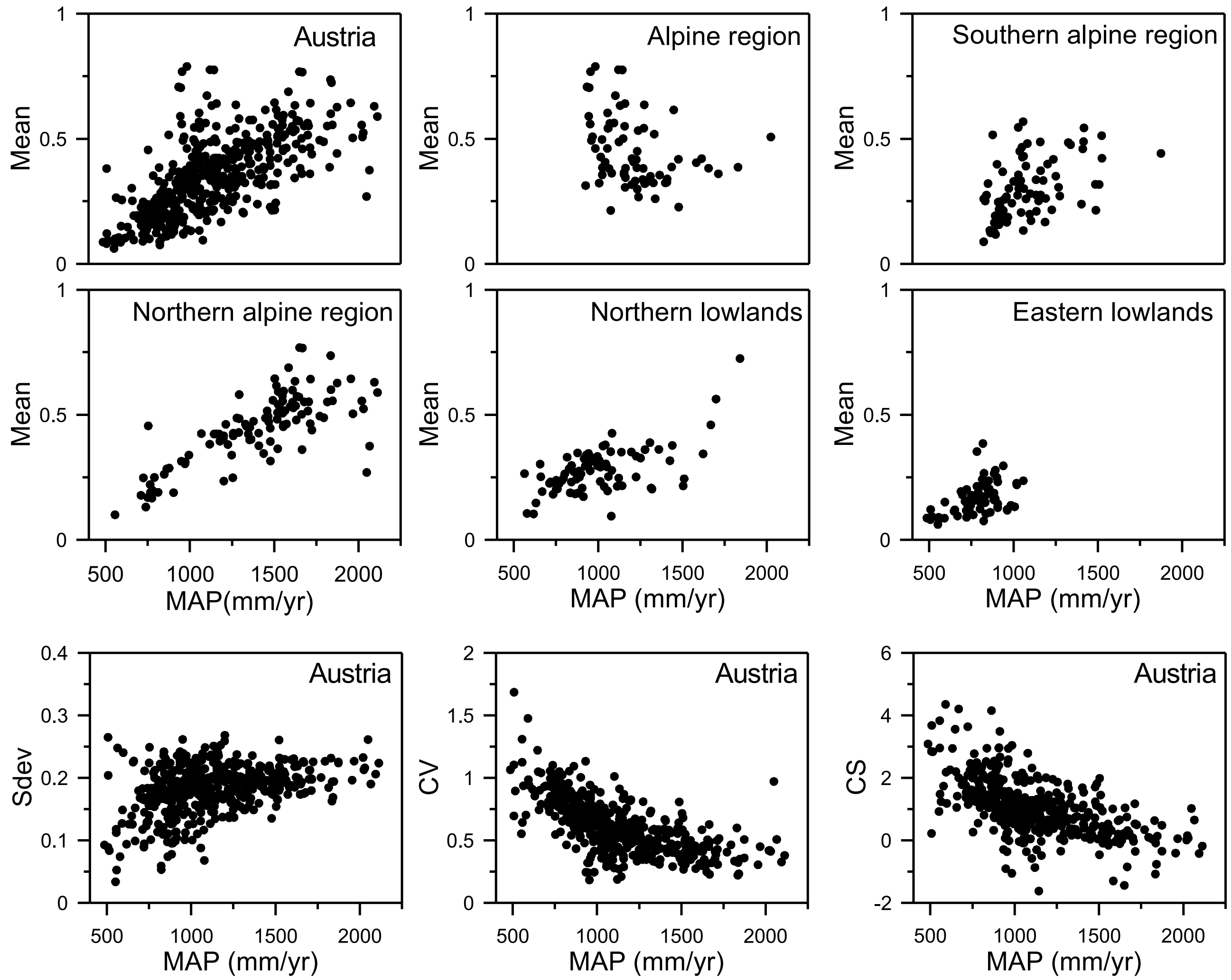

Figure 4. Statistical moments of event runoff coefficients plotted against mean annual precipitation. Each point represents a catchment (after *Merz and Blöschl* [2008a]).

soil depth and interception tend to be small because of the alpine vegetation cover, which increases direct runoff. Fourth, the steep slopes in high alpine catchments may increase surface flow or fast interflow, which also contribute to direct runoff. Hence catchment elevation deemed to be a predictive indicator of runoff coefficients in an alpine environment. There is an obvious change in hydrological behavior from lowland catchments to high alpine catchments. However, the correlation of the runoff coefficients and catchment elevation decrease in the two lowland regions (northern and eastern lowlands). In these regions the effect of snow and glaciers, soil depth, vegetation cover and slopes on runoff generation with increasing altitude is lower and hence the predictive power of catchment elevation decreases.

[38] Rather low correlations are found for the runoff coefficients and the percentage of a geological unit, land use class or soil type. This suggests that geology, land use class and soil type have only a minor control on the event runoff generation at the catchment scale. Particularly interesting is the low correlation of the SCS curve number and runoff coefficients. The correlation coefficient of mean runoff coefficients, CV and CS and the SCS curve number for all Austria catchments are $r = -0.25$, 0.28, and 0.20, respectively. The low correlation and particular the negative correlation of the mean runoff coefficients to the SCS curve number seem to be at variance with the use of the SCS curve number method in engineering hydrology, for predicting runoff coefficients in ungauged catchments. One would expect large curve numbers to be associated with large runoff coefficients and low curve numbers with low runoff coefficients. To analyze this in more detail, curve numbers were recalculated from the observed rainfall-runoff events. For each event in a catchment, a trial curve number was assumed and adjusted according to the observed 5 day antecedent rainfall. The direct runoff resulting from this curve number was compared to observed direct runoff. The back-calculated curve number was then estimated by minimizing the root mean square error of observed direct runoff and direct runoff from the curve number for each event. One assumption of the SCS curve number (CN) method is that the initial abstraction I_a is proportional to the storage capacity of the catchment S

$$I_a = \lambda S, \qquad (3)$$

where $S = \frac{1000}{\text{CN}} - 10$.

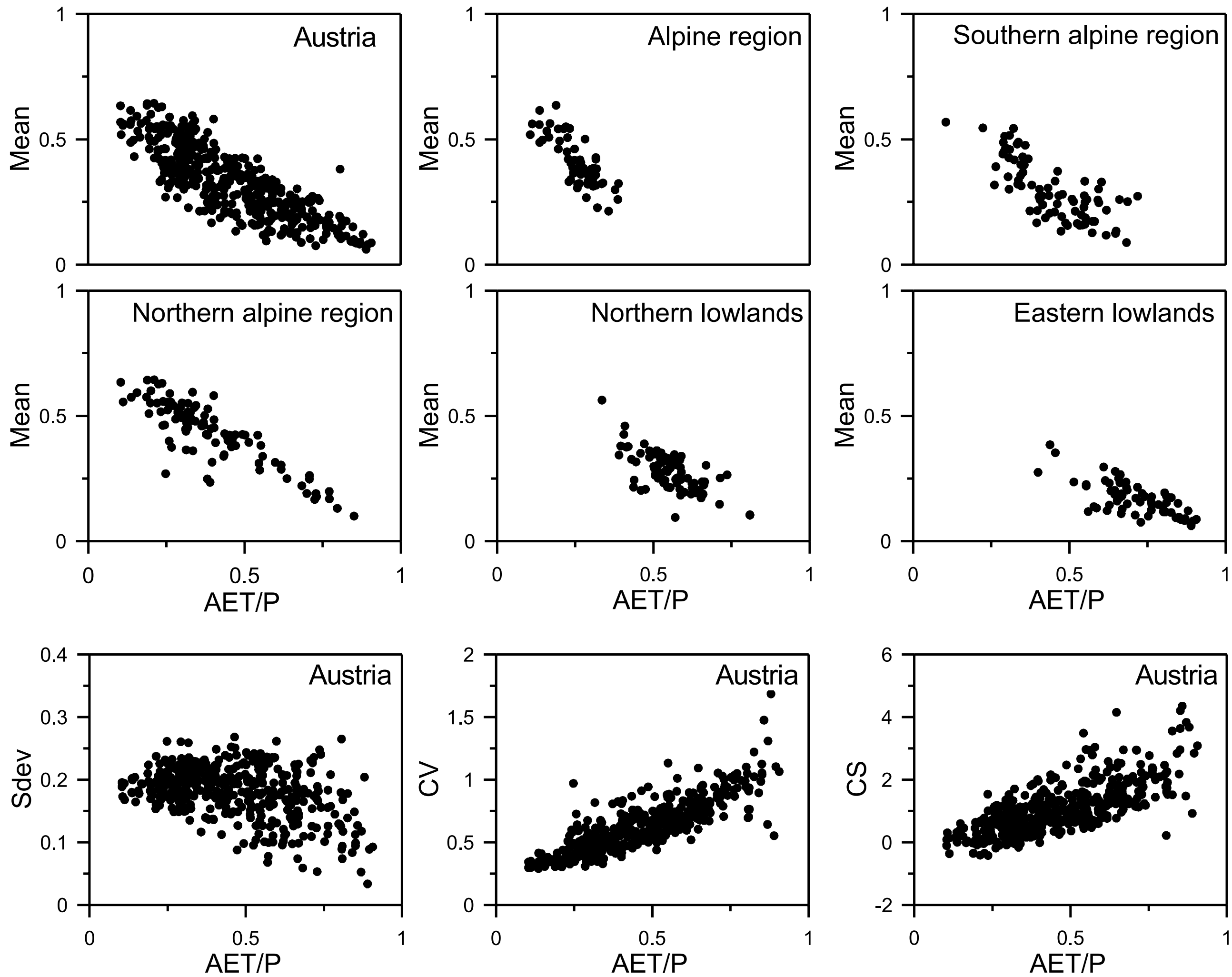

Figure 5. Statistical moments of event runoff coefficients plotted against the long-term ratio of actual evaporation to precipitation (AET/P). Each point represents a catchment.

[39] The U.S. Soil Conservation Service [*Soil Conservation Service*, 1972] proposed $\lambda = 0.2$, which is also adopted in the German guidelines [*Deutscher Verband für Wasserwirtschaft und Kulturbau*, 1985]. *Maniak* [1988, p. 330] argue, that this value is too high for catchment in Central Europe and recommend a value of $\lambda = 0.05$. The Austrian data shows that indeed curve number based on $\lambda = 0.05$ could be better fitted to the observed data. In Figure 8a the curve numbers recalculated from the Austrian rainfall and runoff data are plotted. For comparison the curve numbers estimated from soil type and land use data are plotted in Figure 8b. The two patterns are quite different. The highest back-calculated curve numbers are found for the northern rim of the high Alps (northern alpine region). This is the wettest region in Austria. Orographic enhancement of northwesterly airflows often results in long and persistent rainfall. The catchments tend to be wet and hence runoff coefficients are high. In contrast, low curve numbers are estimated from soil type and land use in that region. The dominant soil type is Rendzina, which is associated with a medium infiltration capacity [*International Society of Soil Science*, 1986] and the region is mainly forested. Because of the assumed high infiltration capacity of forest, the Soil Conservation Service curve number method assigns low curve numbers to the catchments in that region. In the dry lower parts of eastern Austria, the runoff coefficients estimated from soil type and land use are much higher than those back-calculated from observed data.

[40] The high correlation of the statistical moments of the event runoff coefficients to climatic indicators and the low correlation to indicators of geology, land use, soil types and the SCS curve numbers suggest that climate and antecedent soil moisture is a major control on runoff generation in the catchments analyzed here. Climate and antecedent soil moisture vary within the year and hence it is expected that runoff coefficients will also vary within the year. To analyze this in more detail, the seasonal variability of precipitation, actual evaporation, soil moisture, streamflow and runoff coefficients is calculated for each region. Note that the seasonal variability of precipitation, actual evaporation, soil moisture and streamflow are obtained from simulations of the daily catchment water balance [*Parajka et al.*, 2005], while the seasonal behavior of runoff coefficients is obtained from the event analysis. The daily soil moisture state simulated by the model is, of course, dependent on the maximum storage capacity of the soils, which is a calibrated

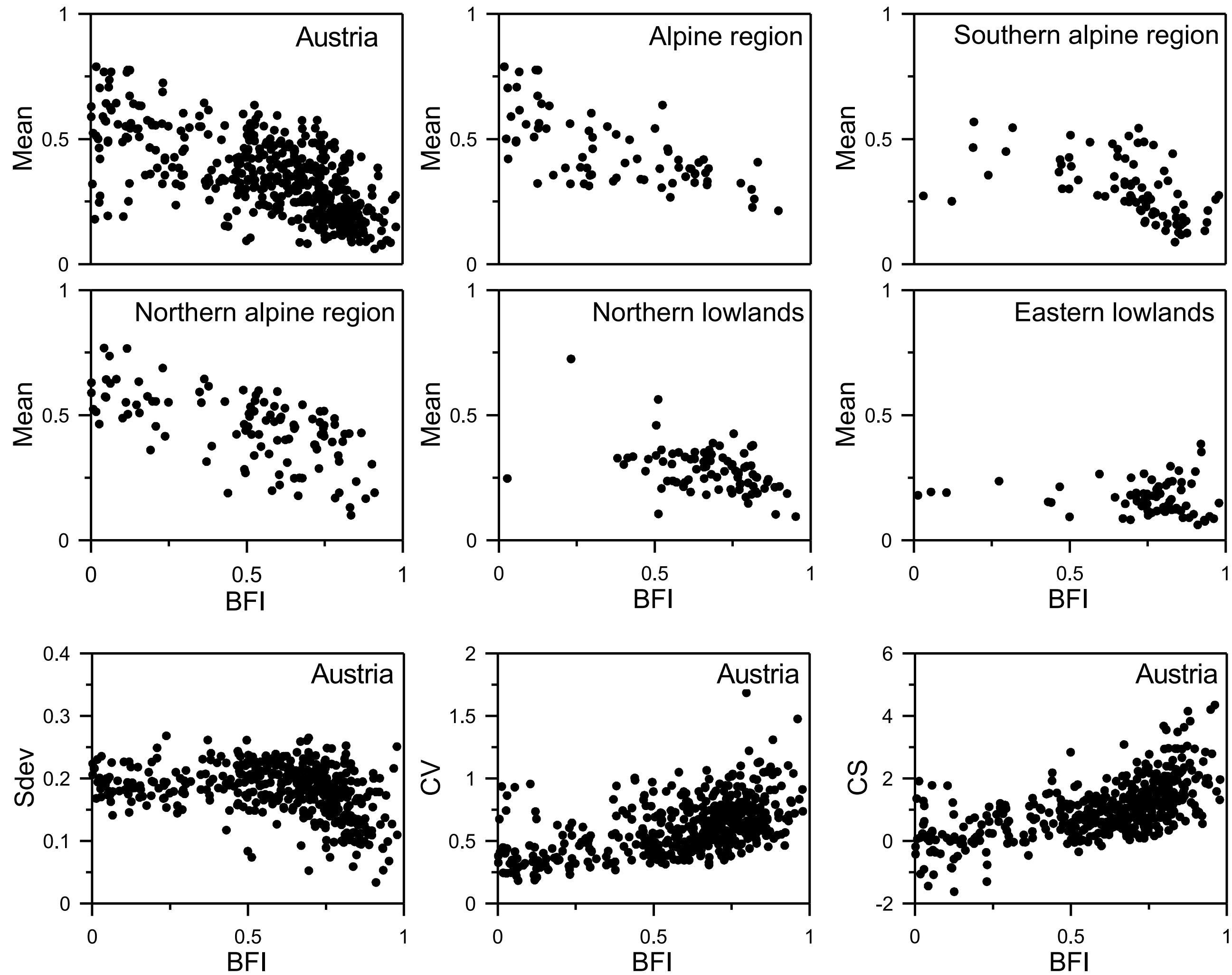

Figure 6. Statistical moments of event runoff coefficients plotted against the base flow index (BFI). Each point represents a catchment.

model parameter. Because of the uncertainty of calibrated model parameters in general, one would expect that the maximum storage capacity and hence the soil moisture will be associated with some uncertainty. However, because of the reasonable results of the daily water balance simulation under different conditions [*Merz and Blöschl*, 2004, *Parajka et al.*, 2005, 2006, 2007a, 2007b], we believe that the relative variability of the soil moisture within the year can be reasonably simulated. To make different catchments comparable, the soil moisture is standardized to zero mean and unit variance

$$\mathrm{SM}^* = \frac{\mathrm{SM} - \overline{\mathrm{SM}}}{\sigma_{\mathrm{SM}}}, \tag{4}$$

where SM* is the transformed soil moisture, SM the soil moisture, $\overline{\mathrm{SM}}$ the mean soil moisture and σ_{SM} is the standard deviation of soil moisture. For each month, precipitation, actual evaporation and streamflow as a percentage of their annual values of each catchment are averaged within a region and plotted against the month in Figure 9. The mean runoff coefficient and the standardized soil moisture for all catchments within a region are also plotted against the month in Figure 9.

[41] For all regions in Austria there is a seasonal variation in precipitation, evaporation, soil moisture and streamflow. Precipitation and, of course, actual evaporation tend to be higher in summer with a maximum of both hydrological quantities in July. Soil moisture exhibits an opposite behavior, with a maximum in winter and a minimum in summer. The seasonal variability of streamflow, however, differs between the regions. In the higher-altitude regions, with a strong influence of glacier melt and snowmelt (alpine, southern alpine, and northern alpine region), the maxima of runoff tend to occur in spring and summer, depending on catchment altitude. In the alpine region, the maxima in streamflow tend to occur in July, while in the lower southern and northern alpine regions the maxima of streamflow tend to occur in May or June. This is clearly related to glacier melt and snowmelt being important processes in these regions. In the northern and eastern lowlands, the maxima in streamflow tend to occur in early spring. The minima in streamflow are in late summer when the catchment soil moisture state is low because of evaporation in summer. The difference in the streamflow seasonality between the alpine

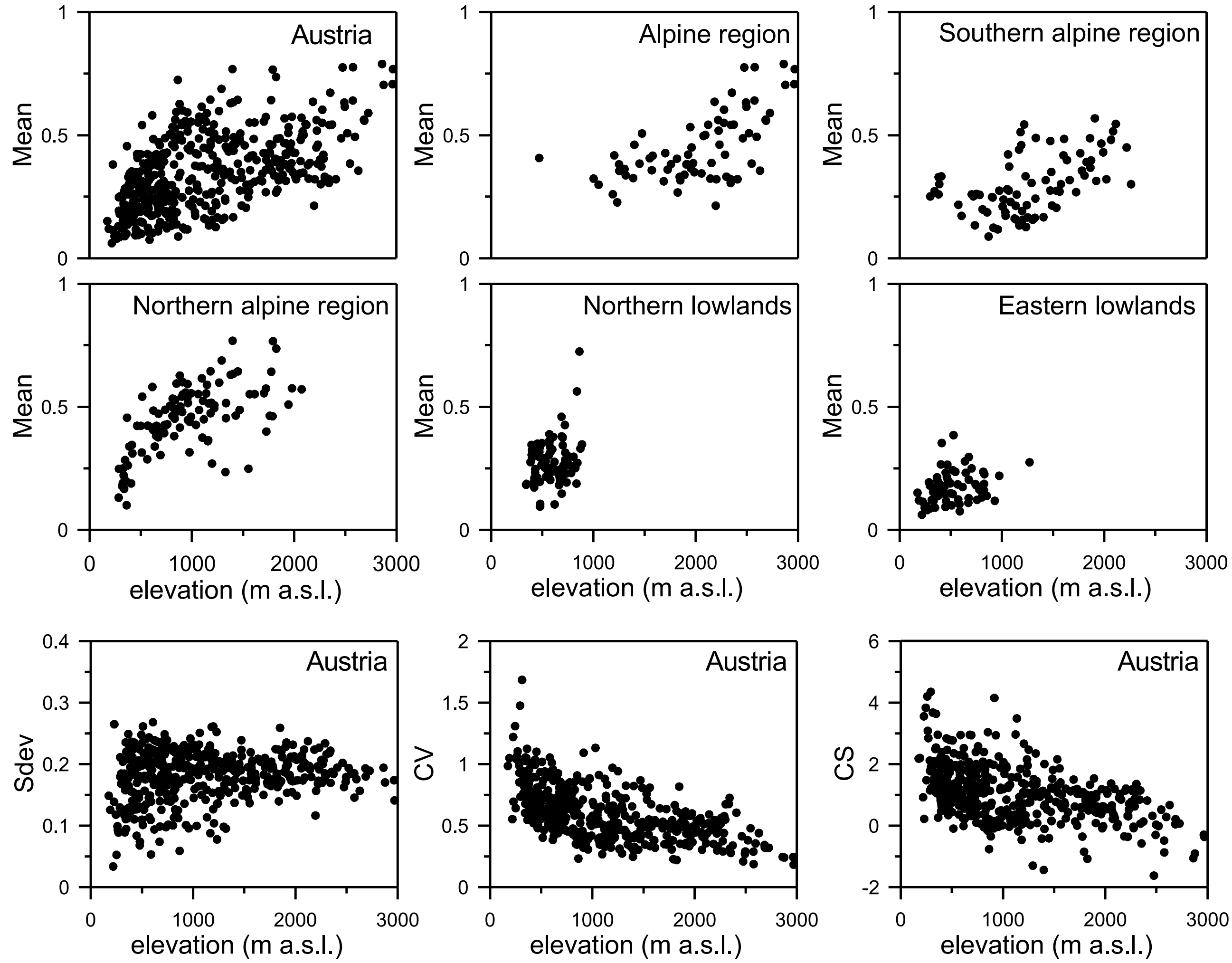

Figure 7. Statistical moments of event runoff coefficients plotted against mean catchment elevation. Each point represents a catchment.

regions and the lowlands can be clearly related to the varying importance of precipitation, glacier melt and snowmelt and evaporation in these regions.

[42] The seasonal variability of runoff coefficients follows the seasonal pattern of soil moisture. The amplitude of the seasonal variability of runoff coefficients and soil moisture is, of course, different, as soil moisture has been standardized by the standard deviation, while the runoff coefficients have not. In winter and spring, when soil moisture is high, the runoff coefficients tend to be high, while in summer, when the catchments are dryer, the runoff coefficients tend to be lower. In the alpine region this decrease in runoff coefficients is later in summer, due to the later glacier melt and snowmelt in higher alpine catchments. The peak in runoff coefficient in autumn in the southern alpine region can be explained by weather patterns from the south, which tends to occur in October or November. These weather patterns carry warm moist air from the Adriatic Sea to Austria and results in large rainfall in the southern rim of the southern alpine region. The large rainfalls are associated with high runoff coefficients and often trigger flood events.

3.2. Controls on the Temporal Variability

[43] The first controls on the temporal variability analyzed in this paper are event rainfall characteristics, i.e., event rainfall depth, maximum rainfall intensity and event duration. As event rainfall characteristics are derived from hourly rainfall time series, the maximum intensity is the highest rainfall depth observed in one hour within each catchment. Event duration is the duration of the rainfall-runoff event, as derived by the event separation methodology described in section 2. Note that the rainfall duration can be shorter.

[44] In Figure 10 the cumulative distribution functions of the relative deviation of the event runoff coefficients from the catchment's mean runoff coefficient for all catchments within a region are plotted. The relative deviation from the mean is given by

$$\Delta = (\mathrm{rc} - \overline{\mathrm{rc}})/\overline{\mathrm{rc}}, \tag{5}$$

where rc is the event runoff coefficient and $\overline{\mathrm{rc}}$ is the mean runoff coefficient of all events in a catchment.

[45] The events are stratified into two classes according to the event condition in comparison to the average catchment

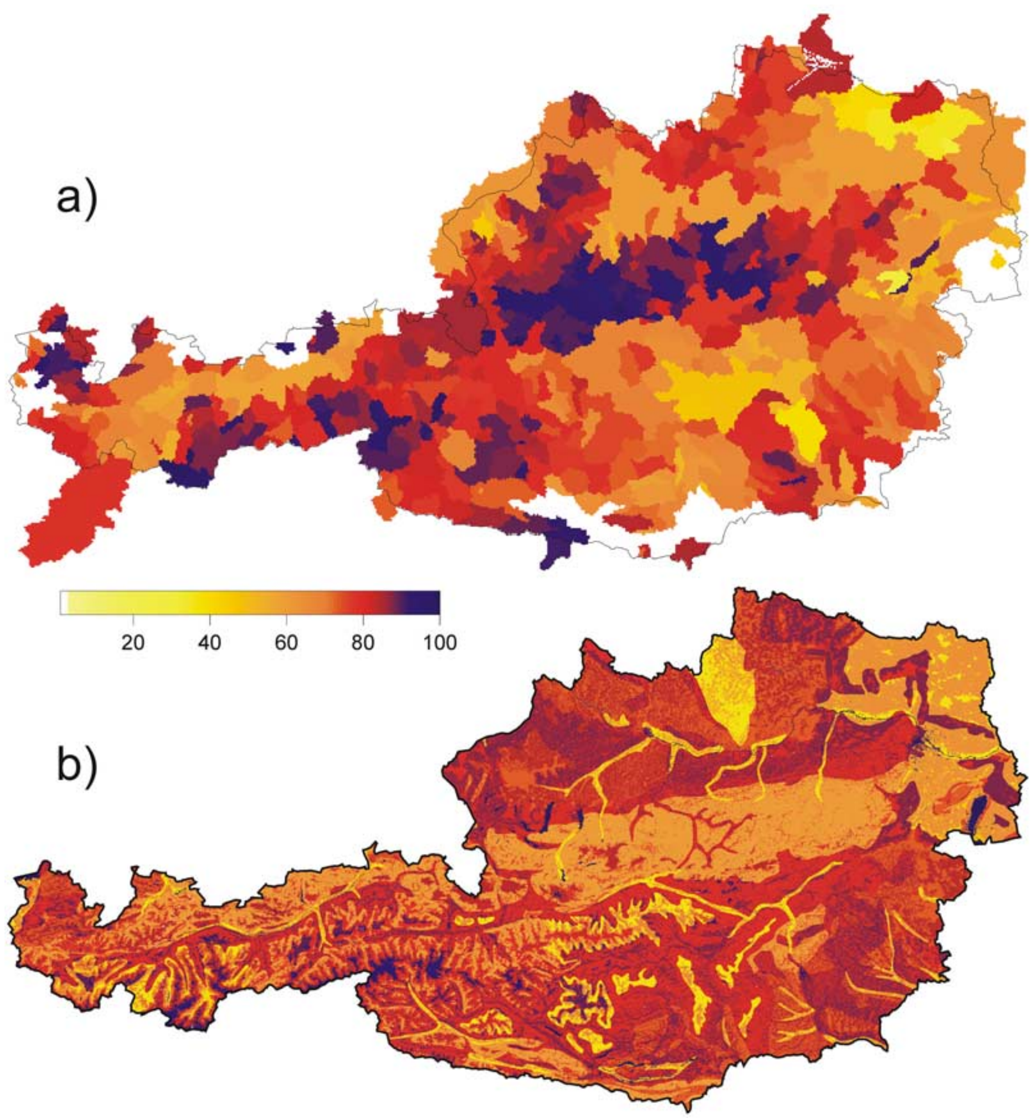

Figure 8. (a) SCS curve numbers back calculated from event runoff coefficients of about 64,000 events for $I_a = 0.05S$, where I_a is initial abstraction and S is the storage capacity of the catchment. (b) SCS curve numbers estimated from soil types and land use data [*Deutscher Verband für Wasserwirtschaft und Kulturbau*, 1984].

conditions. For example, runoff coefficients of events with an event rainfall depth lower than the average rainfall depth of all events in that catchment are classified into the class ''low depth'' (Dashed line in Figure 10 (left)), while runoff coefficients of events with an event rainfall depth larger than the averaged event rainfall depth are classified as ''high depth'' (Solid line in Figure 10 (left)).

[46] The analysis of the Austrian data suggests that the event rainfall depth is not a major control on the runoff coefficients as the cumulative distribution functions of the relative deviation from the mean stratified by event rainfall depth higher and lower than averaged event rainfall depth are quite similar. The analysis of the maximum event intensities (Figure 10 (middle)) indicates that rainfall events with lower maximum rainfall intensity tend to have higher runoff coefficients. This is counterintuitive but can be related to the Austrian rainfall characteristics. A large number of events with high runoff coefficients are caused by long and persistent rainfall events, while only few events with high runoff coefficients are caused by short but intensive rainfall bursts. This is corroborated by the analysis of the event duration (Figure 10 (right)). Events of longer duration tend to have higher runoff coefficients than shorter events. It is also likely that the lack of dependence between rc and intensity is related to the scale of the catchments analyzed. The median catchment size is 133 km^2. It is likely that for smaller catchments a more pronounced relationship to intensity would appear.

[47] The analysis of the controls of the spatial variability of runoff coefficients suggests that antecedent soil moisture is a major control on runoff coefficients. The controls of antecedent soil moisture at the event scale are shown in Figure 11 (left). For all regions in Austria, as well as for the entire Austrian data set, events with a higher soil moisture state than average soil moisture state tend to have higher runoff coefficients. The difference between the two cumu-

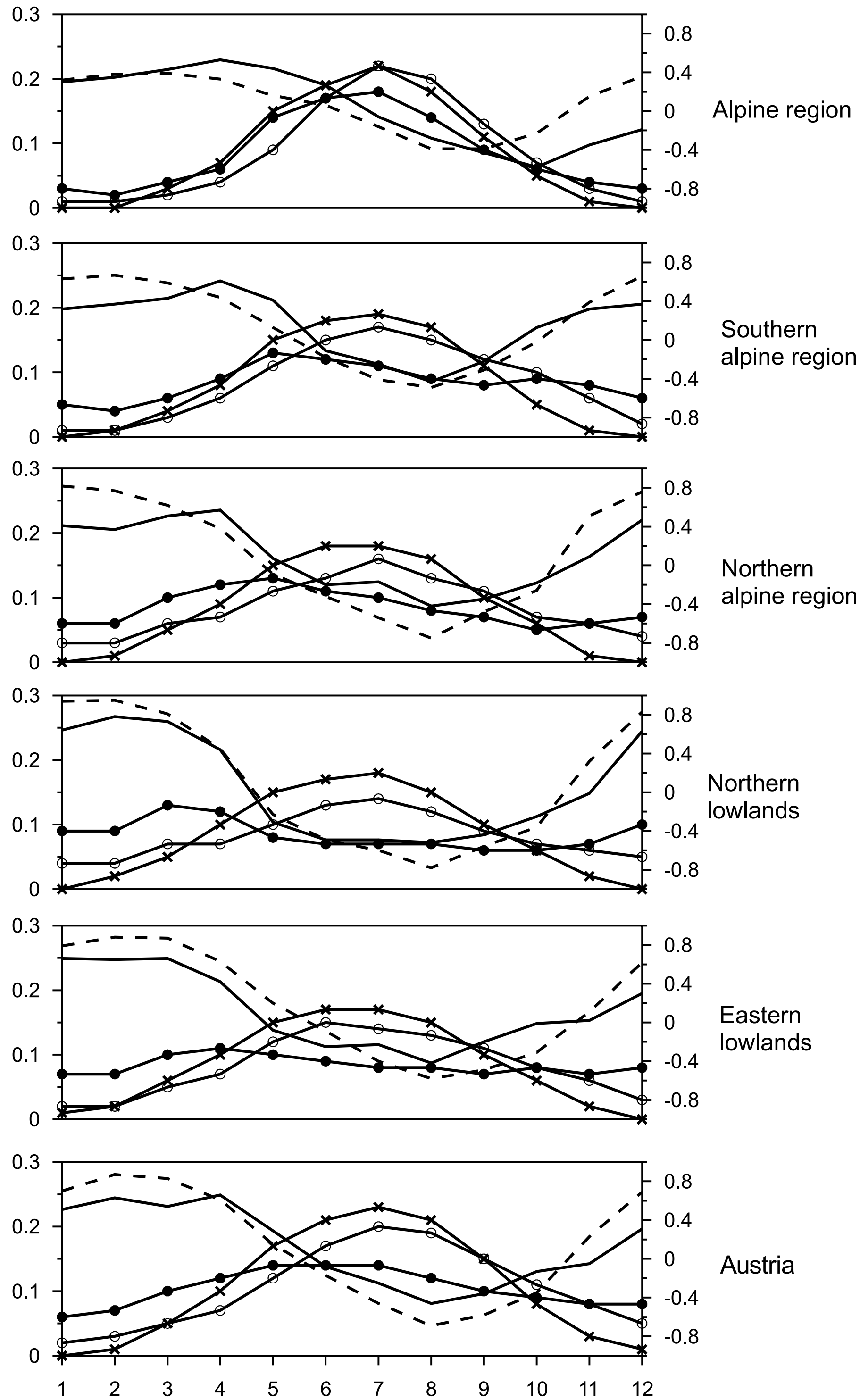

Figure 9. Long-term mean monthly precipitation (open circles), evaporation (crosses) and runoff (solid circles) as percentage of their annual values. Event runoff coefficients (solid line) and standardized soil moisture (dashed line) are plotted as deviates from the mean on the right axis.

lative distributions is particular large in the dry lowlands of Austria (northern lowlands and eastern lowlands). In these regions event rainfall is usually too low to significantly increase soil moisture and hence the event runoff coefficients during the event. The soil moisture state prior to the rainfall-runoff event seems to much more rule the runoff generation.

[48] In many Austria catchments the runoff regimes are strongly affected by snow processes [*Parajka et al.*, 2005]. Thus the effect of an existing snow cover on the resulting runoff coefficients is analyzed. In Figure 11 (middle) the cumulative distribution is stratified by events with a positive snow water equivalent (SWE) on the day the event starts, and events without snow. The snow water equivalent was

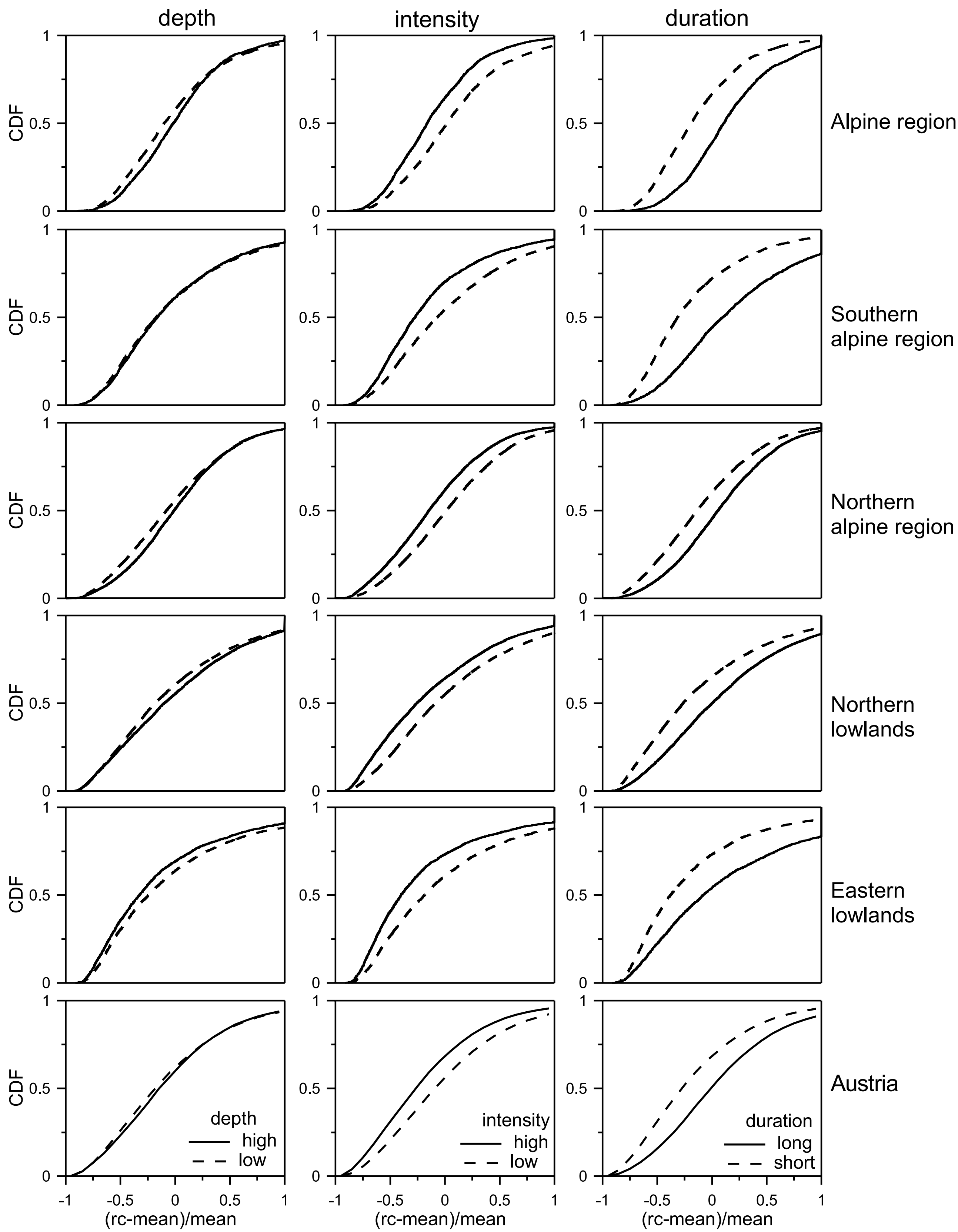

Figure 10. Distribution function of event runoff coefficient deviates stratified by (left) small (dashed lines) and large (solid lines) event rainfall depth, (middle) lower (dashed lines) and high (solid lines) maximum event rainfall intensity, and (right) shorter (dashed lines) and longer (solid lines) rainfall duration.

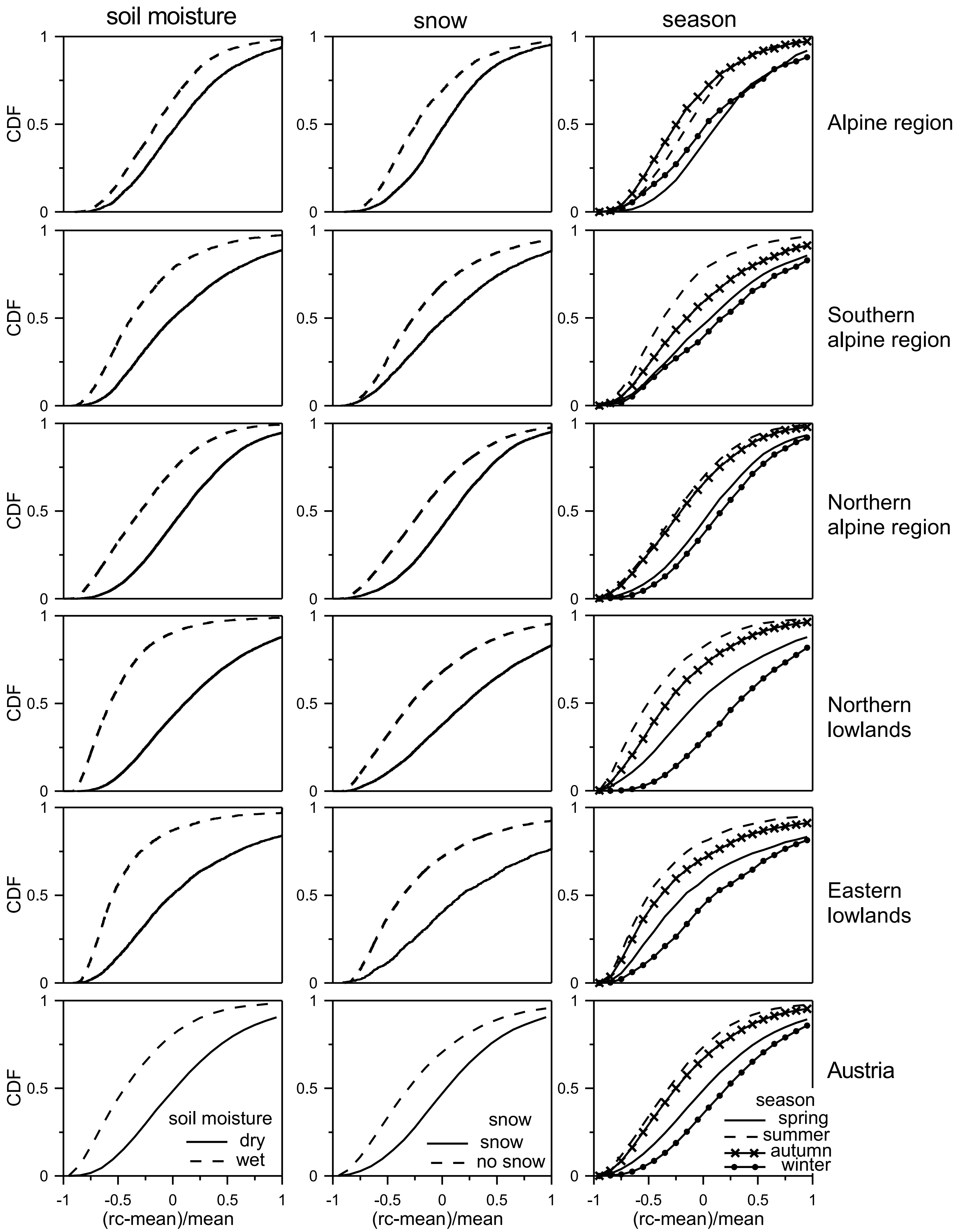

Figure 11. Distribution function of event runoff coefficient deviates stratified by (left) dry (dashed lines) and wet (solid lines) soil moisture, (middle) without (dashed lines) and with snow cover (solid lines), and (right) season.

estimated by simulating the daily water balance using a semidistributed conceptual catchment model [*Parajka et al.*, 2005]. For events, where a snow cover exists (SWE > 0) the runoff coefficients tend to be larger than for events without snow. Similar to the antecedent soil moisture, the difference in the cumulative distribution functions are particular large in the dryer regions of the northern and eastern lowlands.

[49] The increased runoff coefficients during snow cover periods result from snowmelt and rain on snow events. Snowmelt usually occurs over a number of days with increasing snowmelt rates during this period as air temperatures increase and the snow gets gradually wetter. Over this period, the catchment wets up so that even relatively small melt rates can lead to high runoff rates. Additional rainfall on the wet soils and snow covered area then results in large runoff coefficients.The distribution function in Figure 11 (right) shed more light on the seasonal distribution of the runoff coefficients. With the exception of the alpine region, winter is the season with the highest runoff coefficients, and summer is the season with the lowest runoff coefficients. In the three alpine regions (southern alpine, northern alpine, and alpine region) winter and spring runoff coefficients are almost identical while in the two lowland regions winter runoff coefficients are significantly larger. Clearly this is related to earlier snowmelt in the lowlands as compared to the alpine regions.

[50] Information of antecedent soil moisture is often not available and antecedent rainfall is widely used as an indicator of soil moisture [e.g., *Soil Conservation Service*, 1972]. In Figure 12 the cumulative distribution functions of the relative deviation for 5, 10 and 30 day antecedent rainfall are plotted. For all regions in Austria, events with higher antecedent rainfall tend to have higher runoff coefficients. The difference between the lower and higher antecedent rainfall curve is somewhat higher for 5 and 10 days antecedent rainfall than for 30 days antecedent rainfall. Not surprisingly, antecedent soil moisture (Figure 11) is a much better indicator or runoff coefficients than is antecedent rainfall (Figure 12).

4. Discussion and Conclusions

[51] The analyses indicate that the catchment antecedent soil moisture state is the dominant control on event runoff coefficients for the climates and catchment scales examined in this paper. This can be concluded from both types of analysis, the analysis of the spatial and the analysis of the temporal variability.

[52] In the analysis of the spatial variability of runoff coefficients, the highest correlations of mean runoff coefficients, Sdev, CV, and CS are found for indicators representing the catchment wetness state such as the long-term ratio of actual evaporation to precipitation and mean annual rainfall. In dry catchments runoff coefficients tend to be small and they are highly skewed. Because of the small mean values of the distribution, CV tends to be large. In wet catchments event runoff coefficients tend to be high and the distribution function is almost uniform. Because of the larger mean values, CV tends to be lower than in drier catchments.

[53] The highest correlation coefficients of the runoff coefficient moments are found for the long-term ratio of actual evaporation to precipitation. AET/P is a measure of long-term water input and output of a catchment, and hence it is an indicator of water storage in the soils. Similarly, a high correlation is found for mean annual precipitation. The important control of antecedent soil moisture on runoff coefficients is also apparent in by the seasonal analysis of the hydrological quantities (Figures 9 and Figure 11 (right)). The seasonal behavior of the runoff coefficients is quite similar to the seasonal variability of soil moisture. In winter to spring, when soil moisture is high, runoff coefficients tend to be high, while in summer, when catchments are dryer, the runoff coefficients tend to be lower. There are also important differences between the regions related to the earlier snowmelt in the lowlands than in the Alps. The analysis of the temporal variability also corroborates the importance of antecedent soil moisture. The two cumulative distribution functions of event runoff coefficients stratified by the antecedent soil moisture state are much more different than the cumulative distribution functions stratified by event rainfall depth or maximum event rainfall intensity.

[54] This suggests that for this type of climate and catchment scale the differences in runoff formation due to varying antecedent soil moisture is much larger than the increase in the runoff coefficient during a rainfall event. A similar result has been found by *Kohl and Markart* [2002], who analyzed rainfall sprinkling tests on Austrian hillslopes. They found only a slight increase in surface runoff coefficients between 30 and 100 mm/h rainfall, while the seasonal variation in runoff coefficients at the same site, which may be related to seasonal soil moisture variation, is much larger. The importance of antecedent soil moisture on the runoff coefficients is also corroborated by the analysis of runoff coefficients of maximum annual floods stratified by different flood causing mechanisms by *Merz and Blöschl* [2003]. They found, that the largest runoff coefficients occur for snowmelt floods and long rain floods, both associated by wet antecedent conditions. The analysis also indicates that soil moisture derived from soil moisture accounting schemes has more predictive power for the temporal variability of runoff coefficients than antecedent rainfall. Initial conditions are likely to affect runoff volume for most runoff generation types; in Hortonian runoff through reducing infiltration capacity, in saturation excess runoff through expanding contributing areas, and in macropore flow and subsurface stormflow through connecting preferential flow paths [*Merz and Plate*, 1997; *Zehe and Blöschl*, 2004]. In most of the catchments of the study area runoff generation likely occurs by a mix of these mechanisms.

[55] Initial conditions are not always found to closely drive runoff response. There are examples in the literature where runoff volumes seem to be insensitive to antecedent soil moisture and mainly controlled by event precipitation. An example is the study of *Kostka and Holko* [2003], who analyzed runoff response of a mountainous catchment in Slovakia. They suggested that the lack of sensitivity of runoff response to soil moisture is related to the role of the riparian zone in runoff generation. *Scherrer et al.* [2007] found, that the sensitivity of runoff coefficient on antecedent soil moisture depends on the dominant runoff processes. Hortonian overland flow is hardly affected; while subsurface flow dominated catchments reacted quite sensitively to antecedent wetness.

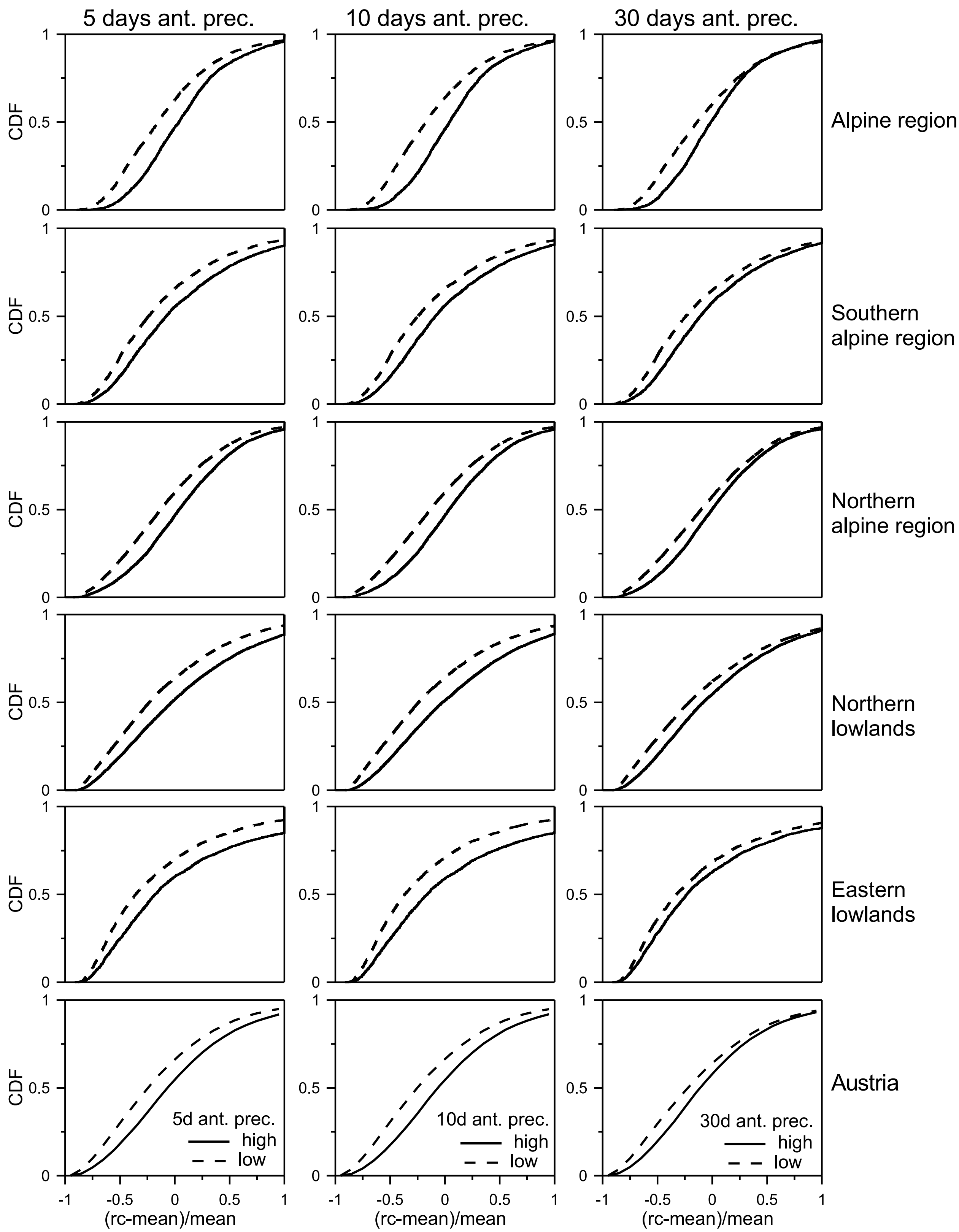

Figure 12. Distribution function of event runoff coefficient deviates stratified by (left) lower (dashed lines) and higher (solid lines) 5 day antecedent rainfall depth, (middle) lower (dashed lines) and higher (solid lines) 10 day antecedent rainfall depth, and (right) lower (dashed lines) and higher (solid lines) 30 day antecedent rainfall depth.

[56] It is interesting that *Gottschalk and Weingartner* [1998] interpreted the Swiss runoff coefficients mainly by topographic characteristics such as altitude and slope and to some degree by stream network density and geology. Also in the alpine part of Austria a strong correlation of the runoff coefficients with altitude and slope is apparent, as altitude in alpine environments is a surrogate measure for rainfall, glacier and snow effects, soil depth and vegetation cover. Rainfall tends to increase with elevation and hence alpine catchments tend to be wetter, resulting in higher runoff coefficients. Also, snow cover and glaciers tend to increase runoff coefficients. The steep slopes in high alpine catchments may be conducive to surface or fast interflow, which contribute to direct runoff. The high alpine catchments tend to have a shallow soil depth and interception is usually small because of the alpine vegetation cover, which also increases direct runoff. There is an obvious change in the runoff generation processes between high alpine and lower altitude catchments, which appears to result in a strong correlation of runoff coefficients with altitude and slope for the entire Austrian data set. In the lowland regions (northern lowlands and eastern lowlands), the predictive power of topographic indices is lower than for all of Austria. Clearly, in these regions other controls such as evaporation are more important.

[57] While climate and antecedent soil moisture seem to be very important in controlling the runoff coefficients, land use, soil types and geology do not seem to exert a major control as the correlation of the mean runoff coefficients to these catchment characteristics are rather low. Particular interesting is the low correlation of the mean runoff coefficients and the SCS curve numbers found for the Austrian data. This result needs to be interpreted in the context of the data set used. The main differences in the patterns of the SCS curve numbers where found for the northern rim of the high Alps, where rainfall is large because of orographic enhancement. This is the wettest region of Austria and hence runoff coefficients tend to be high. However, catchments in that region are mainly forested which is associated with small curve numbers in the SCS method. Forest cover is usually assumed to enhance interception because of large leaf areas, which may affect smaller events. More important for larger events is the observation of higher permeabilities and hence lower runoff coefficients of forest soils, compared to, e.g., agricultural land, assuming similar antedecent conditions [e.g., *Markart et al.*, 2006]. However, for the Austrian conditions, it seem that the variability in climate and hence antecedent soil moisture mask these effects and land use and soil type do not seem to be good predictors of runoff coefficients at the catchment scale.

[58] The low correlation of runoff coefficients and land use and soil type may also be related to scale. Most of the catchments analyzed in this study are medium- to large-sized catchments. Once one moves to smaller-scales, particularly hillslopes, soils and land use clearly become more important as illustrated by numerous plot-scale studies [e.g., *Kirnbauer et al.*, 2005]. Some of the land use and soil characteristics are likely to average out over the catchment size analyzed in this paper. Also, *Cerdan et al.* [2004] noted that the spatial arrangement of areas of a given land use within a catchment will be important for runoff coefficients at the catchment scale.

[59] A third reason for the apparent low predictive power of geological, soil and land use indices may be the use of the percentage of catchment area covered by a given geological unit, soil and land use type to characterize the process controls on the runoff coefficients. Although this is the type of information typically used in many practical studies, it seems not to be representative as even within the same geological unit, soil or land use type, the runoff generation can differ vastly, depending on infiltration capacity, preferential flow through macro pores, cracks or rills etc. as illustrated by many case studies around the world [e.g., *Wösten et al.*, 2001]. An example of the problematic nature of percent geology in hydrological analyses is given by *Merz and Blöschl* [2008b] (Figure 6). It is likely that more detailed soils data that include hydraulic characteristics will have better explanatory power of the runoff coefficients. However, such explanatory data set are not available at the regional scale.

[60] The results of the analysis suggest that climate and antecedent soil moisture driven by the seasonal water balance of catchments are the main control on the spatio-temporal variability of runoff coefficients in Austrian catchments. It is suggested that better methods are needed for estimating runoff coefficients in ungauged catchments that account for these processes in this type of environment.

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