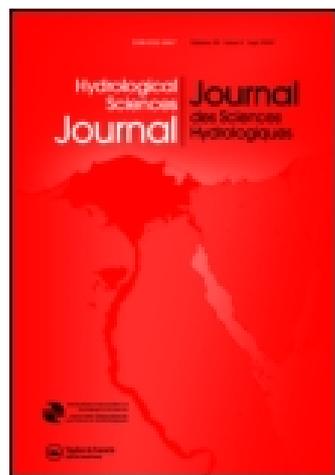


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Linking streamflow drought to the occurrence of atmospheric circulation patterns

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Linking streamflow drought to the occurrence of atmospheric circulation patterns

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Abstract The growing use of surface water resources calls for more intense research on low flow causes and characteristics. This paper presents an investigation linking regional streamflow drought to the occurrence of atmospheric circulation patterns (CPs). Streamflow drought events of 74 basins in southern Germany were determined using the threshold level approach. The regional classification of the basins through a cluster analysis of the drought series provided the basis for the definition of a regional drought index and the following investigation of the influence of CP occurrence on drought. Frequency cross-tabulation showed several high-pressure and anticyclonic CP types to be strongly associated with streamflow drought in southern Germany. The influence of these CPs on streamflow drought was quantified using a logistic regression model. The model results revealed important regional differences concerning the time lag of the drought response and the relevant CPs.

Etude sur les relations entre les étiages et les types de circulation atmosphérique

Résumé L'accroissement de l'usage des eaux de surface exige de s'intéresser aux causes et aux caractéristiques des étiages. Cet exposé présente une analyse de l'influence des types de circulation atmosphérique (CPs) sur les étiages. Les périodes d'étiage de 74 bassins versants du sud de l'Allemagne ont été définies par un seuil de débit. Ces bassins versants ont été classifiés selon leurs séries d'étiages. On a défini un indice régional de sécheresse, qui a été relié aux fréquences d'apparition des types de circulation atmosphérique. Pour toutes les régions les étiages ont pu être associés à des types de circulation atmosphériques caractéristiques, en particulier aux circulations atmosphériques de haute pression et de type anticyclonique. L'influence de ces types de circulation atmosphérique a finalement été analysé à l'aide d'un modèle de régression logistique calculant la probabilité d'un étiage en se basant sur l'histoire des circulations atmosphériques. La variabilité des délais entre les signaux atmosphériques de sécheresse et les étiages est essentiellement d'origine régionale.

INTRODUCTION

The knowledge of the causes and characteristics of periods with water deficit are very important for sustainable water resources management, especially in low flow periods. Extreme low flows are critical for the ecology of a river system, especially where river flow is directly used for industrial, agricultural or domestic purposes. In addition to the growing dependency of the world's population on surface water, another reason for studying streamflow drought is that it integrates the water deficit signal found in other hydrological parameters. The understanding of the propagation of the water deficit through the hydrological cycle can still be improved.

Most of the research dealing with the coupling of atmospheric and hydrological systems has focused on the downscaling of large-scale GCM output, which can then be used as an input to regional hydrological models. The classification of atmospheric circulation patterns and circulation indices has proven to be a successful tool in

establishing a direct stochastic link with hydrological parameters. Close relationships between streamflow anomalies and indices based on Sea Level Pressure such as the El-Niño Southern Oscillation (ENSO) were described by Dracup & Kahya (1994) and Piechota & Dracup (1996). Redmont & Koch (1991) carried out a study relating the Pacific North America Index (PNA) to precipitation, temperature and annual streamflow. Significant correlations between atmospheric circulation and streamflow anomalies were computed. A recent investigation in Europe by Shorthouse & Arnell (1997) showed a strong link between the North Atlantic Oscillation Index (NAOI) and average monthly runoff. Strong spatial patterns in the investigated relationship could be delineated across Europe.

The aforementioned studies describe the effect of known continental-scale atmospheric circulation on regional-scale seasonal or annual meteorological and hydrological averages. Another approach to link synoptic meteorological parameters to regional or local phenomena, focusing on higher time resolutions, is the weather generator principle. Bárdossy & Plate (1991) presented a stochastic rainfall model conditioned on daily CPs. The model was extended by a spatial covariance function for the simulation of the daily local probability and the spatial amount of precipitation (Bárdossy & Plate, 1992). A similar approach was adopted by Wilby (1993) and Wilby *et al.* (1994) for coupling Lamb's Weather Types with a conceptual rainfall-runoff model and a hydrochemical model in an experimental basin in the UK. The results indicate that the frequencies of floods and droughts depend on the synoptic scenario. Periods of prolonged anticyclonic activity experience the lowest flows (Wilby *et al.*, 1994).

Only a few studies have addressed the direct relationship of these hydrological extremes to circulation patterns. Duckstein *et al.* (1993) linked daily CP occurrences to partial duration series of floods in Arizona, USA. Groups of flood-producing CPs could be determined and their seasonally varying contribution was analysed. The monthly Bhalme-Mooley Drought Index (BMDI) has been modelled as a CP-conditioned first-order autoregressive stochastic process (Bogardi *et al.*, 1994). Pesti *et al.* (1996) presented an alternative method to predict regional monthly values of Palmer Drought Index (PDI) using a fuzzy rule. The dependency of streamflow drought on atmospheric circulation has frequently been mentioned in the literature (e.g. Tallaksen *et al.*, 1997). However, the specific interrelationship of streamflow-derived drought parameters and atmospheric circulation patterns has not been studied. The objective of the present study is to investigate the influence of atmospheric circulation pattern occurrence on streamflow drought and to evaluate different methods which link the two phenomena.

DATA AND STUDY AREA

The study area is situated in the southern part of Germany, in a region with varied landscapes and hydrological regimes. The streamflow data were taken from the European Water Archive (EWA) and the drought spells were calculated applying the threshold level approach based on the theory of runs introduced by Yevjevich (1967). The analysis was applied to daily streamflow records of 74 small basins (10 km² to 500 km²). Drought spells were determined as run length below the threshold for the time series from 1962 to 1992. The Q₉₀ (discharge exceeded for 90% of the time) was

chosen as threshold level. Previous studies carried out in the same area have shown its suitability (Demuth & Heinrich, 1997; Demuth & Külls 1997). Successive (dependent) droughts were pooled as far as an inter-event excess volume of 10% of the deficit volume of the previous drought was not exceeded or did not last longer than a day (Tallaksen *et al.*, 1997). The drought events were calculated and all further investigations were then carried out separately for the summer (May–October) and the winter (November–April) season.

The atmospheric circulation patterns (CPs) European “Grosswetterlagen” according to Hess & Brezowsky (1977) were used for representation of the synoptic meteorology. This classification by the German Weather Service (Deutscher Wetterdienst, DWD) is based on the mean air pressure distribution over Europe and the northern Atlantic Ocean. The classification initially distinguishes zonal, meridional and mixed circulation. Subtypes specify the movement direction of frontal zones and the location of high and low pressure area centres as well as cyclonic or anticyclonic rotation. This scheme leads to the definition of 29 circulation patterns (and one

Table 1 The European “Grosswetterlagen” (circulation patterns, CP) (after Hess & Brezowsky, 1977).

Circulation type		No.	Description	Abbreviation	
Major type	Sub-type				
Zonal circulation	W	1	West, anticyclonic	Wa	
		2	West, cyclonic	Wz	
		3	Southern West	WS	
		4	Angleformed West	WW	
Mixed circulation	SW	5	Southwest, anticyclonic	SWa	
		6	Southwest, cyclonic	SWz	
	NW	7	Northwest, anticyclonic	NWa	
		8	Northwest, cyclonic	NWz	
	HM	9	Central European high	HM	
		10	Central European ridge	BM	
Meridional circulation	TM	11	Central European low	TM	
		N	12	North, anticyclonic	Na
	13		North, cyclonic	Nz	
	14		North, Iceland high, anticyclonic	HNa	
	15		North, Iceland high, cyclonic	HNz	
	16		British Isles high	HB	
	17		Central European trough	TRM	
	NE		18	Northeast, anticyclonic	NEa
			19	Northeast, cyclonic	NEz
	E	20	Fennoscandian high, anticyclonic	HFa	
		21	Fennoscandian high, cyclonic	HFz	
		22	Norwegian Sea–Fennoscandian high, anticyclonic	HNFa	
		23	Norwegian Sea–Fennoscandian high, cyclonic	HNFz	
		24	Southeast, anticyclonic	SEa	
S	25	Southeast, cyclonic	SEZz		
	26	South, anticyclonic	Sa		
	27	South, cyclonic	Sz		
	28	British Isles low	TB		
	29	Western Europe trough	TRW		
	Unclassified	U	30	classification not possible	U

undefined CP) that belong to three major circulation types and ten subtypes (Table 1). A circulation pattern generally persists for several days while the entailed weather features remain constant. The transition to the following circulation pattern takes place rapidly. Due to the availability of long time series of data (since 1881), the European “Grosswetterlagen” are well suited for climatological studies.

Weather in Germany is influenced to a high degree by cyclones from the North Atlantic Ocean moving westward across the country. These cyclones tend to vanish towards the east. Orographic rainfall is the governing precipitation generating mechanism. Convective rain during summer time also plays an important role.

For southern Germany (Fig. 1), the characteristics of the headwater regions of the Rhine and Danube continental river basins vary considerably. Snow strongly influences the water balance of the steep alpine basins in the most southern part of the area. A hilly landscape of glacial and fluvial deposits characterizes the Pre-Alps. The western part of the study area features the forested mountain ranges of the Black Forest in the south and the lower altitude ranges of the Odenwald, Spessart and Rhön further north. Along the eastern part of the study area, the ridge of the Bavarian Forest mountain range outlines the German border. North of the river Danube dominates the karstic range of the Swabian and Franconian Alb. The northern part of the study area is characterized by a hilly landscape (Gäu) with dominating agricultural land use and small forested highland ranges (Keuper) of various sedimentary geological facies.

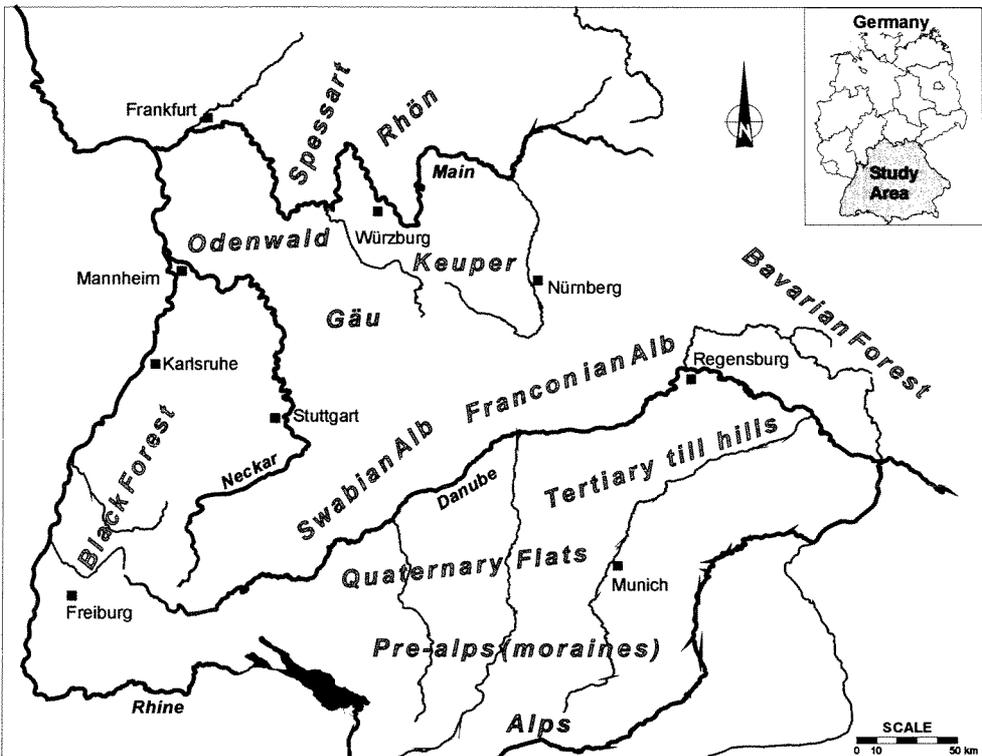


Fig. 1 Study area.

METHODOLOGY

Considering the gradual development of a streamflow deficit and neglecting the “noise” of the rainfall data, it was directly investigated how the atmospheric drought signal is passed on to the variability of the streamflow component in the hydrological cycle. Droughts are regional in nature (Tallaksen *et al.*, 1997) and the implication, that CP-induced hydroclimatological effects (weather) are strongly influenced by regional geography, suggests the use of a regional drought description. The strong regional patterns of different hydrological responses to a certain synoptic situation found in other studies (e.g. Dracup & Kahya, 1994; Shorthouse & Arnell, 1997) strongly support this reasoning. An aggregation of the basin information to the regional scale was therefore carried out previous to the investigation of the CP–drought relationship. The following steps were executed in this study:

- Regional classification of basins using drought series
 - (a) Drought spells were calculated from streamflow records of 74 basins.
 - (b) A cluster analysis was performed to classify the basins according to similar drought parameters. The drought time-series of the basins that form a cluster were then aggregated to derive a regional (cluster) drought index (*RDI*).
- Linking regional drought and CP occurrence
 - (a) Cross-tabulation of CP frequencies and drought periods identified which CPs were significantly associated with drought.
 - (b) Groups of CPs with similar effect concerning drought were extracted from these results.
 - (c) A logistic regression analysis was performed to quantify the influence and the contribution of the CP-group occurrences to drought spells.
- The comparison of the results for the different clusters allowed an interpretation with respect to regional features during all stages of the study.

REGIONAL CLASSIFICATION

A cluster analysis was performed in order to find homogeneous groups of basins concerning streamflow drought duration and occurrence. Based on the drought spells computed with the threshold level approach, each day was assigned a binary code (drought was denoted as one and no drought as zero) thus implying the relevant information about drought duration and occurrence time. The cluster analysis was carried out on the histories of these daily drought indicator variables (*DI*) of the basins. Binary Euclidean Distance served as the measure to determine the similarity of two basins. For cluster formation the hierarchical agglomerative algorithm of the Ward Method which minimizes the distances within a cluster was chosen (Everitt, 1980).

A jump in the agglomeration schedule suggests the ten cluster solution. The homogeneity of the groups was then tested using additional similarity measures (e.g. Jaccard Index). Cluster 4 shows the highest homogeneity with each pair of basins having an average of 67% of their drought days simultaneously. With only 30% of simultaneous drought days, Cluster 8, which contains only three basins, is the least homogeneous. Although the classification algorithm was solely based on drought occurrence data, the clusters are geographically coherent (Fig. 2). This spatial

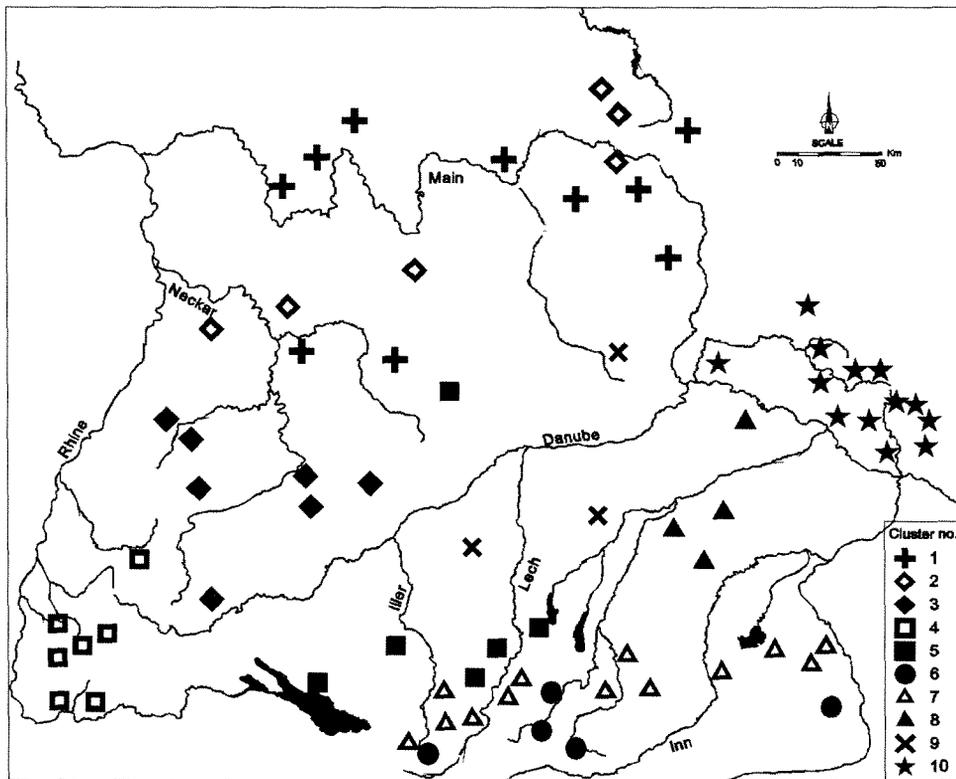


Fig. 2 Spatial classification of the basins according to the result of the cluster analysis.

classification consequently provides a suitable basis to investigate the regional streamflow response to the CP occurrence.

The cluster-averaged streamflow regimes and drought regimes (mean number of drought days per month) illustrate the hydrological characteristics of the ten clusters (Fig. 3). Two clusters describe the alpine regions at higher (C6) and lower (C7) altitudes with low flow conditions in winter caused by the snow storage. The region exhibits a high degree of seasonality and low inter-annual variation of low flows (Demuth & Heinrich, 1997). Another cluster distinguishes the pre-alpine moraines (C5) from the flat areas of quaternary glacio-fluvial deposits (C9) and the hilly areas of tertiary till deposits (C8). The region's equable streamflow regimes with low flow periods in summer follow the annual rainfall and evapotranspiration cycle. Hydrological drought can occur at every time of the year. The higher in altitude these regions are located, the stronger are they influenced by snow. Consequently, the higher basins feature more drought days during winter time and the summer maximum is shifted towards autumn. The flow regimes found in the Bavarian Forest (C10) and the southern Black Forest (C4), forested mountainous regions in a crystalline geological environment, also exhibit high seasonal flow variability. Although both regions are characterized by spring snowmelt, winter droughts are rare in the Black Forest. The basins of the Swabian Alb (C3), the Triassic hills and lowlands (C2) and the highland areas of the Upper Main region in the northeast (C1) form the three remaining clusters.

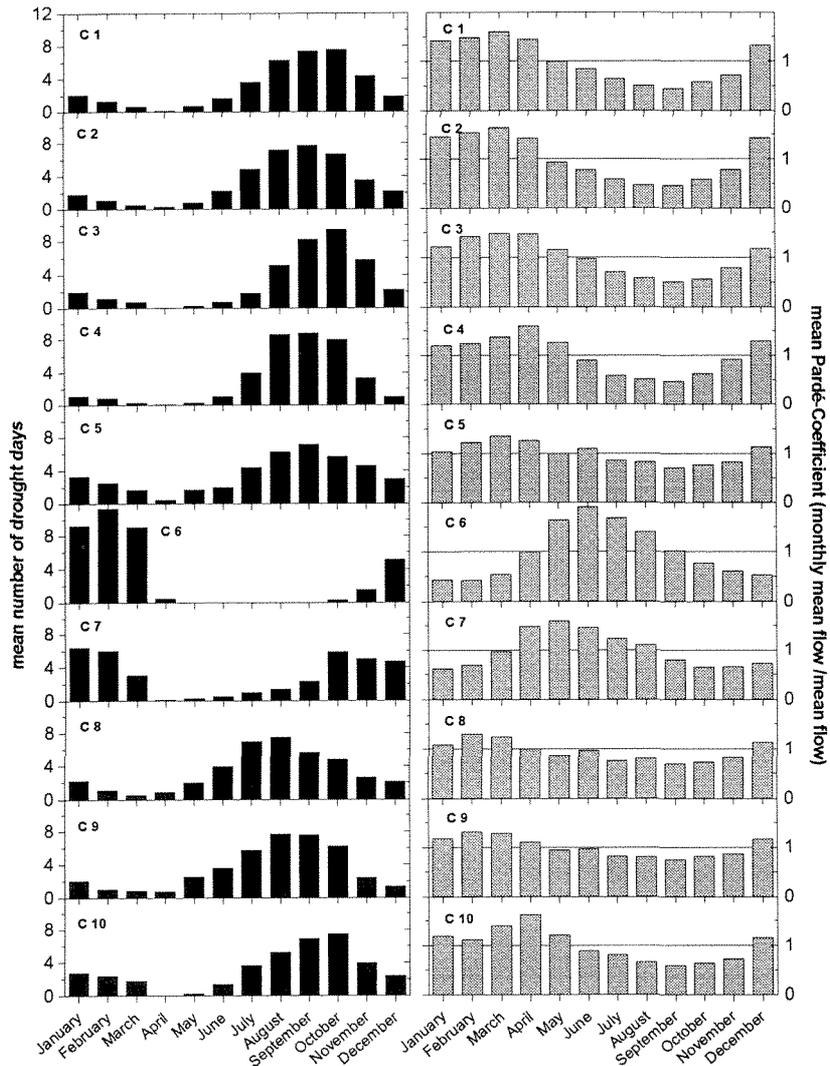


Fig. 3 Hydrological characteristics of the basins: mean drought regimes (left) and mean streamflow regimes (right).

The drought regimes of the two latter regions show a gradual rise towards their autumn peak while Black Forest and Swabian Alb are characterized by a jump to higher absolute values in July/August.

The geographical coherence and the presumed relation to geology suggest the potential to define homogeneous drought response regions independently using basin properties. However this procedure requires a detailed regionalization study using high resolution map information. In this study 'regional' is therefore used in terms of the cluster information. The threshold level approach determines dry spells for a single basin. A method to aggregate the drought information of a whole cluster was found by adding the daily drought indicators (*DI*) of its cluster members. After normalization by

the number of basins, a regional drought index (*RDI*) can be defined. Hence, the *RDI* (equation (1)) describes how strong a region is affected by streamflow drought

$$RDI = \frac{1}{n} \sum_{i=1}^n DI \quad (1)$$

where n is the number of basins of the considered cluster and the daily drought indicators (*DI*) take the binary values of zero or one for each basin.

An example of the time series of the regional drought index (*RDI*) is given in Fig. 4. The severe drought period in 1976 illustrates how this index represents the different regional drought conditions. The alpine regions, C6 and C7 were strongly affected by winter drought while the other regions showed prolonged drought periods in summer (e.g. C1 and C4).

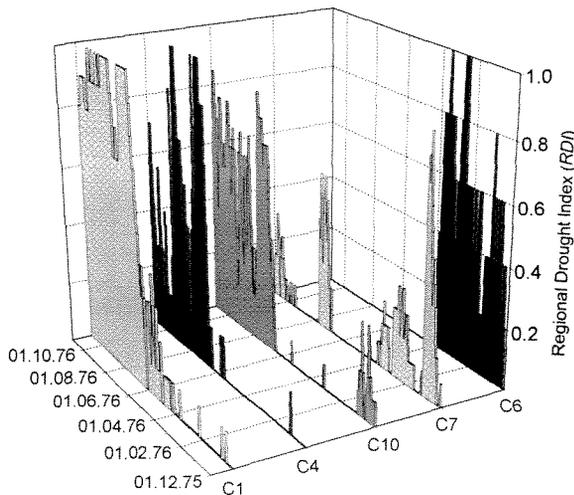


Fig. 4 The 1976 drought.

LINKING REGIONAL DROUGHT AND CP OCCURRENCE

The influence of atmospheric circulation on streamflow drought was investigated in three steps. The methods were applied to each cluster (region) separately in order to evaluate the differences of the regional drought responses.

In the first step, cross-tabulation of CP frequencies and drought index values was used to test the two variables for dependency and to rank the CPs according to their “drought causing” power. Data sets of the two simultaneously occurring daily variables, CP and the regional drought index (*RDI*) provided the basis to examine the relationship. Cross-tabulation analysis is based on the combined frequency distributions of two variables and is suited to investigate the relationship of two variables of non-metric or different scales (Backhaus *et al.*, 1996). Therefore three stages of drought severity based on the regional drought index were defined: $RDI = 0$

(no drought), $0 < RDI \leq 0.5$ (medium drought), $RDI > 0.5$ (severe drought). Frequencies of the CP occurrence during periods of these different drought stages were compiled. Cross-tabulation statistics were tested for dependency of the two variables. The Pearson χ^2 test of independence (equation (2)) examines whether the departure of the observed frequencies from the expected (marginal frequencies) are random. The χ^2 test is defined as:

$$\chi^2 = \sum_{\text{column}} \sum_{\text{row}} \frac{(n_{ij} - \hat{n}_{ij})^2}{\hat{n}_{ij}} \tag{2}$$

where n_{ij} are the observed frequencies and \hat{n}_{ij} are the expected frequencies.

The test supplies information about the probability whether an association between the two variables (CP and *RDI*) exists. The contingency coefficient, *C* (equation (3)), measures the strength of the association. Tables with similar cell number can hence be compared and ranked. The coefficient is defined as:

$$C = \sqrt{\frac{\chi^2}{\chi^2 + N}} \tag{3}$$

where *N* is the total sample size.

The residuals of a table (positive or negative departures of observed from the expected frequencies) finally allow the specification of the direction of this association between drought and CP occurrence. They indicate whether a circulation pattern occurrence frequency during drought is above or below “normal”.

Two different types of tables were calculated for each cluster. Type 1 related the three drought stages (rows) to the 29 CPs (columns). Thus the significance of an existing relationship of CP occurrence and drought periods was determined. Type 2 related the three drought stages (rows) to two columns (one for the occurrence of a specific CP, the other one for the remaining days). Thereby the relationship of each specific CP was tested.

The second step was to find groups of CPs with similar effect to drought. Initially the grouping was based only on the type 2 cross-tabulation results by ranking and grouping the 29 CPs from positive significant (χ^2 test) drought association to negative significant association. Additional information was used to finalise the classification of the 29 CPs, especially to classify some of the less frequent CPs for which no significant relationship with drought was calculated. The criteria were similarity of air pressure patterns and CP-related weather features in Germany, which have been studied by Hess & Brezowsky (1977), Bürger (1958), Bárdossy & Caspary (1990). Each group should then contain CPs with similar drought-association and weather characteristics. This step was necessary to overcome the problem of extremely low frequencies of some of the original CP types. The cross-tabulation analysis was then carried out again with the CP groups to determine their drought association.

In the third step, a logistic regression model was established to simulate the daily probability for a cluster “drought event” by the given CP-group occurrence history. Where the response variable is of the Bernoulli all or nothing (event/no event) type, a logistic link function in a generalized linear model is frequently used (Clarke, 1994). In this case, a day was defined as “event” when the regional drought index (*RDI*) time

series exceeded a certain limit (Fig. 5(a)). The multiple logistic regression model for the probability (P) for an event can be written as (equation (4)):

$$P(\text{event}) = \frac{e^Z}{1 + e^Z} \quad (4)$$

$$Z = B_0 + B_1 X_1 + B_2 X_2 + \dots + B_k X_k \quad (5)$$

where Z (equation (5)) is the linear combination of the independent variables X_i (for $i = 1, \dots, k$), B_0 is the model constant and B_i are the estimated regression coefficients which are determined using an iterative maximum likelihood algorithm (Clarke, 1994).

Following the idea of Pesti *et al.* (1996), *frequency* and *centre of gravity* of the CP-group occurrence within a moving (preceding) time window (Fig. 5(b)) were used as predictor variables. These variables (X_i) represented short-term (daily CP-group), mid-term (30-day lag) and long-term (half-year lag) influences. Daily values were important to indicate whether a drought spell is likely to persist or to be terminated by a CP. For mid-term influences, a constant 30-day window was chosen. Baseflow recession constants were derived from the summer streamflow time series of the studied basins (Demuth & Schreiber, 1994). Using these recession constants, the average duration of hydrograph recession from mean flow (MQ) to $Q90$ was calculated. The calculated values range from 20 to 40 days and consequently suggested the use of a 30-day time lag for the regression model. As many studies have demonstrated the effect of winter circulation on annual streamflow anomalies (e.g. Cayan & Peterson, 1989; McCabe, 1996), long-term atmospheric influences have also to be considered. A half-year lag was therefore chosen to represent how the system was conditioned by the preceding season. Finally, annual cyclic influences that are in particular due to snowmelt and evapotranspiration had to be considered. A variable derived from the mean Pardé-Regime was therefore introduced. As it remains the values of an annual cycle for the entire period, it accounts for the basic seasonal "readiness" of a region for drought.

Three models with different limits to define an "event" were calculated and compared: model 1 with a regional drought index of $RDI > 0$, model 2 for $RDI > 0.33$ and model 3 for $RDI > 0.5$. For the logistic regression, a test that a coefficient is zero was based on the Wald statistic which has a χ^2 distribution. The Wald statistic is the square of the ratio of the coefficient to its standard error (Clarke, 1994). In combination with the goodness of fit, the Wald values were also used to assess the partial contribution of the variables to the model and hence provided valuable information on regionally different influences of CP-group frequencies and time lags. However, they were not suited for an absolute quantification of the regional pattern of dependencies and were therefore treated in a qualitative way.

RESULTS AND DISCUSSION

A significant relationship between CP occurrence and the regional drought indices was found for eight clusters for the summer season and for only three clusters for the winter season. The contingency coefficients (Table 2) from cross-tabulation type 1 showed

Table 2 Contingency coefficients, *C*, of the cross-tabulation of the regional drought index (*RDI*) and CPs (sorted by decreasing contingency).

Summer	<i>C</i>	Winter	<i>C</i>
C4	0.291	C7	0.288
C1	0.277	C6	0.287
C2	0.265	C10w	0.259
C3	0.261		
C5	0.257		
C9	0.235		
C10	0.224		
C8	0.207		

Table 3 Results of the cross-tabulation analysis: significance and direction of the relationship of CP occurrence and regional drought index (*RDI*) per cluster.

Group	Summer CPs	Drought association	Winter CPs	Drought association
I	SEa, HM, HB	++s	SEa, HM, HB, HNa, HNFa	++s
II	BM, HFa	++s	HNz, Nz, HFz	+s
III	Wa, SWa, Sa	+s	SEz, Sz, WW	+s
IV	NWa, HNa, NEa, Na, HNFa	+–	HFa, NEa, BM, Sa	+–
V	NEz, HFz, HNFz	–+	NWa, TB, TRM, SWa, Wa	–+
VI	TRW, WW, SEz, Sz	–	HNFz, Na, NEz, NWz, TM, TRW	–
VII	Wz, NWz, SWz	–(s)	SWz, WS, Wz	––s
VIII	TRM, TB, HNz, WS, TM, Nz	––s		

s χ^2 -test: significant relationship of CP and *RDI* (95% level);

– Residuals indicate (strong – –) negative frequency anomaly during drought;

+ Residuals indicate (strong ++) positive frequency anomaly during drought.

individual CP types that were significantly associated with streamflow drought. Table 3 summarizes these results and shows the CP groups.

The results of the cross-tabulation with the CP groups for the summer period of two exemplary clusters, the Black Forest (C4) and the Pre-Alps (C5) are shown in Fig. 6. The groups represented eight stages from strongly positive (group I) to strongly negative (group VIII) drought association. For the summer half years, high pressure centres over central Europe and the British Isles and anticyclonic CP types with southeasterly and westerly airflow (group I, II), were found to be significantly more frequent and persistent during drought periods. Negative association with drought periods in all clusters was shown by CP groups describing low pressure centres above Europe as well as the southwesterly cyclonic CPs (group VII, VIII). For the winter drought in the three regions under investigation, the highest positive anomalies during droughts are determined for the CP group with northerly and easterly airflow, due to advection of cold air from continental Russia. The differences in significance and direction of drought-associated CPs for summer and winter confirmed the strategy of separate investigations.

The overall performance of the logistic regression models was evaluated by the percentages of days which were classified correctly (Table 4). Predicted probabilities greater than 0.5 were therefore classified as an “event”. Evaluating the model

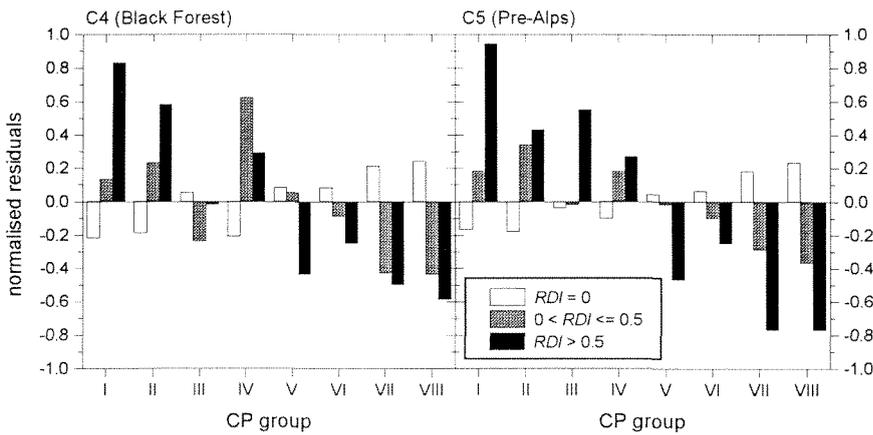


Fig. 6 Residuals of the cross-tabulation of CP groups and RDI.

Table 4 Results of the logistic regression: percentages of days correctly classified as no drought (0), drought (1) and total.

	Model 1			Model 2			Model 3		
	0	1	total	0	1	total	0	1	total
Summer:									
Cluster1	86.9%	75.5%	82.4%	96.0%	58.7%	90.3%	98.0%	55.3%	93.7%
Cluster2	84.5%	73.7%	80.3%	96.8%	68.8%	92.6%	98.0%	70.3%	95.4%
Cluster3	88.0%	74.0%	83.3%	96.3%	62.2%	90.8%	97.3%	63.0%	91.9%
Cluster4	90.3%	72.4%	74.6%	93.7%	54.5%	86.0%	95.5%	45.4%	87.7%
Cluster5	87.9%	53.2%	76.4%	98.2%	24.2%	89.4%	99.0%	22.1%	93.9%
Cluster8	87.6%	51.8%	75.6%	96.8%	26.7%	85.2%	99.7%	14.3%	95.8%
Cluster9	89.1%	54.3%	78.2%	96.2%	48.0%	88.6%	96.2%	48.0%	88.6%
Cluster10	83.9%	69.5%	78.6%	95.7%	48.6%	87.9%	97.3%	35.9%	90.4%
Winter:									
Cluster 6	84.4%	73.7%	80.3%	92.6%	64.5%	85.1%	96.0%	61.3%	89.7%
Cluster 7	80.5%	75.7%	78.4%	96.5%	47.7%	88.6%	98.1%	50.7%	92.7%
Cluster 10w	93.5%	55.5%	84.8%	97.9%	45.1%	91.8%	99.3%	61.8%	96.9%

performance, it has to be considered that for the three models, the original number of event days differed. The percentages therefore represent a relative measure for cluster comparison for the same model.

In the summer season, the classified percentages for the clusters in the western and northern part of the study area (C1 to C4) were highest. Model 1 simulated more than 70% of the event days and the models 2 and 3 still simulated more than 60% for C1 to C3 (Table 4). The western part of southern Germany consequently showed a more pronounced response to atmospheric circulation than the eastern regions. This behaviour corresponds to the influence of central Europe’s dominating westerly airflow decreasing towards the east. An important task of the logistic regression was to distinguish years with severe drought from years without streamflow drought. As the example for summer season and the Black Forest cluster (C4) in Fig. 7 shows, yearly fluctuations of more and less event days were successfully calculated by the Logistic

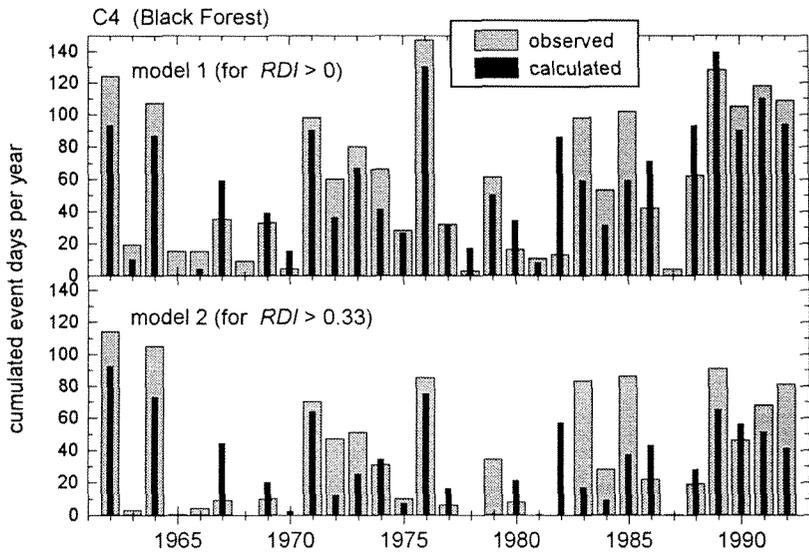


Fig. 7 Cumulated observed and calculated event days per year.

Regression Model. Although underestimated, the best relative estimates were achieved for the most severe drought years. The 1976 drought was especially well simulated for the clusters C2, C4 and C10. The models for these regions included a high contribution of the mid-term frequency variable of CP group VII (western cyclonic CPs, associated with rain), the frequency of which was exceptionally low during this summer. In 1986 drought causing high pressure was dominant but cyclones of group VII also occurred frequently. Consequently, drought could only develop in the eastern clusters where the influence of the cyclones usually ceases. The overestimation of the 1986 drought in the western regions showed that, although the influence of most CP groups was correctly simulated in one year, temporal variability and interactions still cause unexpected responses of the regional drought index (*RDI*) in other years.

For all time lags, the CP groups I and II (high-pressure CPs) showed high contributions to the models. The contributions of the low-pressure CP-group VIII and the cyclic component were also considerable. The latter showed the highest contribution to the models for the Black Forest (C4) and the Bavarian Forest (C10), being highland regions with obviously strong seasonal (snow) influence on the streamflow regime. Instead of introducing the typical annual cycle as an independent variable, a seasonally varying threshold for drought definition could be applied in future studies to understand drought in the sense of a seasonal streamflow anomaly. The direct correlation to CP occurrence can then be expected to be stronger. Considering the partial correlation of the time-lag variables, the prealpine and eastern clusters depend more on long-term influences, whereas the Black Forest (C4) and Bavarian Forest (C10) were more influenced by the mid-term frequencies of the CP groups. This faster streamflow response corresponds to poorer reservoir storage of the crystalline hard rock basins of the latter regions.

The winter drought estimates for the alpine clusters C6 and C7 were successful with more than 70% correctly classified events for model 1. For the lower alpine cluster (C7) and the Bavarian Forest (C10w), the percentages improved with

increasing event-limit of *RDI* in the model. Longer and more persistent winter drought periods in these regions can better be explained by CP occurrence. The high contribution of the regime (cyclic) variable showed that the high altitude of the stations of cluster C6 guarantees a winter freeze every year. Years without drought were not calculated accordingly by the models.

CONCLUSION

The result of the cluster analysis for the regional classification of the basins strongly supports the idea that spatial and temporal variability of streamflow drought in southern Germany is influenced by geographical and topographical location and the underlying geology. The link to atmospheric circulation, including movement direction of frontal zones and associated weather patterns, could explain these hydrological response patterns. It was shown that periods of prolonged streamflow drought in southern Germany were caused by the frequent and persistent occurrence of certain circulation patterns. High pressure over central Europe (HM, BM) and the British Isles (HB) and anticyclonic CPs (Wa, SWa), especially those with easterly air flow (SEa), were strongly associated with summer streamflow drought in all regions. For the alpine and prealpine regions, Foehn-causing CPs demonstrate the same influence. Negative association with summer drought was found for West cyclonic CPs, especially for the western highland ranges and for several low pressure CPs for all of southern Germany. Winter streamflow drought periods were associated with CPs that import cold air from eastern continental regions. Cold and snow producing CPs, however, do not seem to be sufficient to cause extreme low flows. Marked dry climatic conditions also contributed to prolonged winter drought periods. Further investigations and considerations of the physical processes responsible for winter droughts are necessary.

The logistic regression analysis revealed more important regional differences. The Black Forest basins, for example, were most sensitive to the “west” CPs and reacted more to the short- to mid-term influences. This behaviour corresponds to the known high streamflow variability in these steep basins dominated by hard rock. On the contrary, the response of the pre-alpine basins with their large aquifers of unconsolidated till sediments strongly depended on long-term meteorological history. This delay of the atmospheric drought signal explains that for these regions, the cross-tabulation analysis, which only considers simultaneous CPs (and thus short-term influence), determined somewhat different CPs to be responsible for streamflow drought occurrence than the logistic regression using the mid- and long-term variables. An objective way of grouping the CP types focusing more on the hydroclimatological effects of the studied region would further improve the results.

The results demonstrate a considerable influence of synoptic meteorology on streamflow drought. The statistical linkage of the two phenomena promises great forecasting potential for a region with homogeneous drought characteristics. Future studies for drought prediction should consider an adjustment of the relevant time lags between atmospheric signal and drought response to deterministic hydrological parameters.

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