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Investigating the influence of atmospheric circulation patterns on regional streamflow drought in southern Germany

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Abstract This study investigated the influence of synoptic meteorology on streamflow drought in a region with highly variable hydrological characteristics. First, groups of catchments with similar drought characteristics were identified by cluster analysis. A regional drought index (*RDI*) derived from aggregating the streamflow drought series of a cluster provided the basis for the link to the occurrence of atmospheric circulation patterns (CPs). Frequency cross-tabulation revealed important information about the regionally different influence of CPs on drought events. Based on the results of the cross-tabulation, the CPs were classified and reduced to eight groups. Finally, the possibility of simulating the regional drought index by CP-group occurrence was tested using a logistic regression model. The results show that high pressure over central Europe and the British Isles as well as anticyclonic CPs with easterly air flow were strongly associated with summer streamflow drought in all regions.

INTRODUCTION

The knowledge of processes causing hydrological drought and its spatial variability is essential for a sustainable water resources management. Extreme low flows can have an impact on the ecology of a river system, especially where river flow is also used for industrial, agricultural or domestic purposes.

In Europe, the synoptic meteorology is represented either by the North Atlantic Oscillation Index (NAOI) or weather patterns classified from the air pressure distribution above Europe and the North Atlantic Ocean. An investigation by Shorthouse & Arnell (1997) showed a strong relationship between the NAOI and the average monthly runoff of European rivers. Wilby *et al.* (1994) coupled 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 upon the synoptic scenario. Periods of prolonged anticyclonic activity are related to the lowest flows (Wilby *et al.*, 1994). Several "weather generator" studies have used European "Grosswetterlagen" (circulation patterns) for rainfall prediction in Germany (e.g. Bárdossy & Plate, 1992).

Several studies have demonstrated a stochastic link of hydrological variables to atmospheric circulation patterns or indices to be a promising analysis and simulation tool. However, the direct influence of atmospheric circulation on streamflow drought has not been studied widely, although a qualitative relationship has often been mentioned in the literature (e.g. Tallaksen *et al.*, 1997). The present study investigates the influence of synoptic meteorology on streamflow drought in a region with highly variable hydrological characteristics. The analysis focuses on the variability of streamflow drought responses to the large-scale atmospheric signal and discusses the regional characteristics on which the response depends.

REGIONAL DROUGHT DEFINITION

Streamflow drought events of 74 catchments in south Germany were determined by applying the threshold level approach (Yevjevich, 1967) to daily streamflow values of a time period from 1962 to 1992. The $Q90$ was chosen as the threshold to define the drought spells to be consistent with previous studies carried out in the same area (Demuth & Külls 1997; Demuth & Heinrich, 1997). Consecutive droughts were pooled when the inter-event volume did not exceed 10% of the previous deficit volume or did not last longer than a day (Tallaksen *et al.*, 1997). All investigations were carried out for the summer season (May–October).

Based on this drought definition, the time series of each catchment was converted to daily binary indicator values DI (1 for drought, 0 for no drought). In order to find groups of catchments that were homogeneous with regard to simultaneous occurrence and duration of streamflow drought, these series were then subjected to cluster analy-sis. Pairwise similarity was defined by binary Euclidean Distance and the hierarchical agglomerative algorithm of the Ward Method was applied for the clustering (Everitt, 1980).

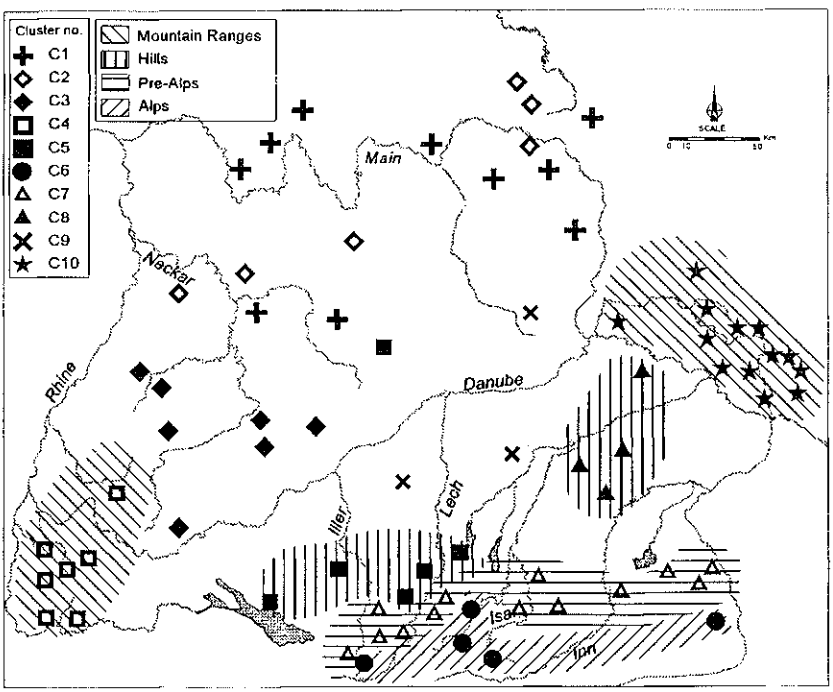

Fig. 1 Catchment classification in south Germany (10-cluster solution). Clusters marked by patterns show best agreement with geographical and geological regions.

The ten-cluster solution revealed the best result for the regional classification (Fig. 1). The marked clusters keep best accordance with geographical and geological regions within south Germany. These are the Black Forest mountain range of crystalline rocks (C4) in the most southwestern part of the study area, two clusters in the alpine regions at higher (C6) and lower (C7) altitudes, a cluster distinguishing the pre-alpine moraines (C5) and the tertiary hills (C8), and the mountain range of the Bavarian Forest (C10) in the east. The catchments of the remaining clusters also show spatial patterns.

Since the resulting clusters show strong spatial coherence, they are suited to provide the basis for an aggregated regional (cluster) drought definition. A regional drought index (*RDI*) was consequently defined as the daily sum of the catchment drought indicators (*DI*) normalized by the number of catchments (*n*) in the cluster :

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

ANOMALY OF CIRCULATION PATTERN FREQUENCY DURING DROUGHT

The atmospheric circulation patterns (CPs) used in this study are known as European "Grosswetterlagen" (Hess & Brezowsky, 1977) and are monitored by the German Weather Service (Deutscher Wetterdienst—DWD). The classification is based on the mean air pressure distribution over Europe and the Northern Atlantic Ocean. Table 1 shows the classification scheme, which results in 29 CPs. A circulation pattern generally persists for several days while the entailed weather features remain constant.

To determine anomalies of CP occurrence frequencies during periods of prolonged streamflow drought, CP frequencies and *RDI* were cross-tabulated. Hence, frequencies of CP occurrence during periods of three stages of drought severity in a cluster, $RDI = 0$ (no drought), $0 < RDI \leq 0.5$ (medium drought), $RDI > 0.5$ (severe drought), were calculated and compared to the expected (1961–1992 mean) CP frequencies. A detailed description of this analysis is given in Stahl & Demuth (1999).

As some of the CPs are too rare for statistical analysis, it was necessary to group them. Based on the anomalies during drought found by the cross-tabulation analysis, the 29 CPs were classified and reduced to eight groups. Information on related hydro-climatological parameters (Bürger, 1958) and typical weather characteristics of the CPs given by Hess & Brezowsky (1977) accomplished and validated this classification. The groups finally contain CPs with similar effect regarding drought.

The CP frequency anomalies during drought periods in region C4 are shown in Fig. 2. However, the grouping was derived from the respective results for all clusters. Group I shows the strongest positive anomaly and group VIII shows the strongest negative frequency anomaly during summer drought. The χ^2 test was used to determine whether these anomalies indicate a significant association between CP occurrence and drought (Stahl & Demuth, 1999). The results for all clusters demonstrate that high pressure over central Europe and the British Isles as well as anticyclonic CPs with easterly air flow (group I and group II) are strongly associated with summer streamflow

Table 1 The European "Grosswetterlagen" (Hess & Brezowsky, 1977).

Circulation type Major type	Subtype	No.	Description	CP
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
	TM	11	Central European low	TM
Meridional circulation	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
		25	Southeast, cyclonic	SEz
	S	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

drought in all regions. Negative association with summer drought was found for north and west cyclonic CPs (group VI and group VII) for mountain ranges that cause orographic rainfall, whereas during low pressure CPs (group VIII) no droughts occurred in the south of Germany.

LOGISTIC REGRESSION ANALYSIS

In the next step, a logistic regression analysis was performed to test the possibility of describing the regional drought index *RDI* (dependent variable) for each cluster by CP occurrence (independent variable). A logistic regression model was established to calculate the probability for regional drought by CP-group occurrence. The multiple logistic regression model for the probability (*P*) for an event can be written as equation (2):

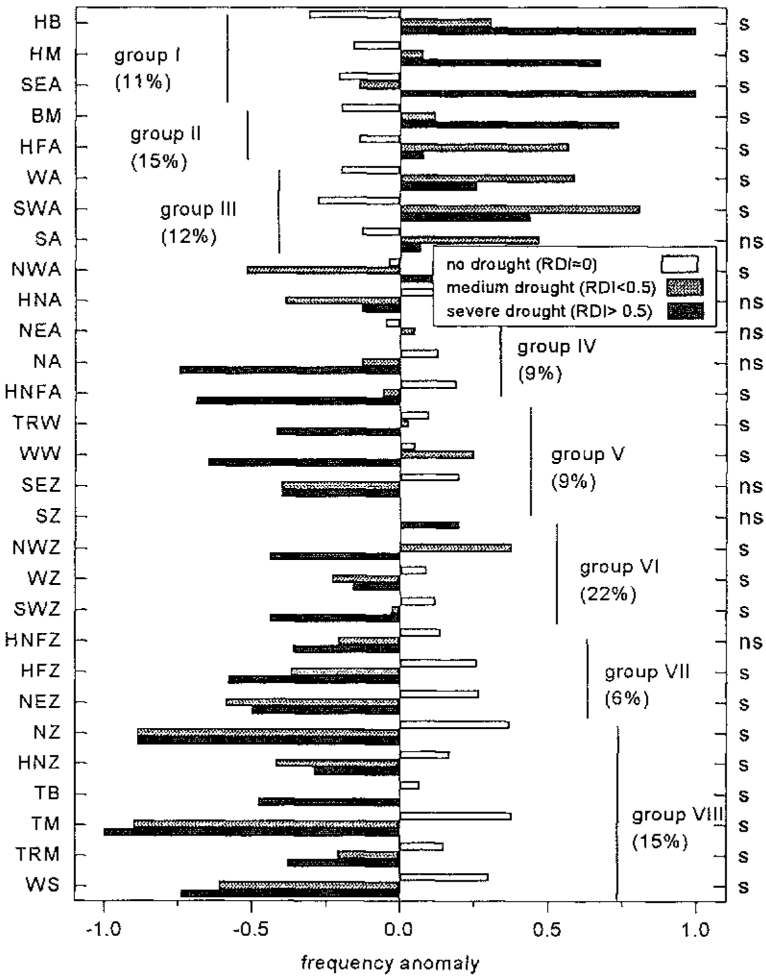

Fig. 2 Residuals of cross-tabulation analysis: left axis—circulation patterns; right axis—significant (s)/non-significant (ns) drought association. CP-group classification is indicated (mean yearly occurrence frequency of groups in %).

$$P(\text{event}) = \frac{e^z}{1+e^z} \tag{2}$$

$$Z = B_0 + B_1 \cdot X_1 + B_2 \cdot X_2 + \ldots + B_k \cdot X_k \tag{3}$$

where Z (equation (3)) is the linear combination of the independent variables X_i (for $i = 1, ..., k$), 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).

The dependent variable in a logistic regression is of the Bernoulli (event or no event) type (Clarke, 1994). In this study, two models with different limits of defining an "event" from the *RDI* series were calculated and compared: model 1 for *RDI* > 0, model 2 for *RDI* > 0.33. 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 defined as 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. Model performance and the contribution of the variables allow the investigation of the regionally different influence of CP groups.

Derivation of independent variables

Simultaneous daily CP-group occurrences (as investigated in the first section of this paper by cross-tabulation) are important in indicating whether a drought spell is likely to persist or to be terminated by a CP. However, the mid- and long-term CP history of the drought onset is also important. Working towards the forecasting of drought events, it is necessary to know more about the time lag between the atmospheric drought signal and the streamflow drought response.

Previous studies in the same area have analysed baseflow recession constants (Demuth & Schreiber, 1994). Calculating the duration of hydrograph recession from mean discharge to *Q*90 gives an average time of 30 days, which can be interpreted as the dry weather period that is necessary to cause streamflow drought in the catchments. Hence, within this first investigation, CP frequencies during a moving (preceding) 30-day time-window were chosen as variables to represent mid-term influences. Since many studies have demonstrated a considerable influence of winter circulation on annual streamflow anomalies (e.g. McCabe, 1996), long-term atmospheric influences also had to be considered. A half-year lag represents how the system was conditioned by the preceding season. Finally, an average Pardé-Regime for each cluster was calculated to account for the general seasonal cycles of e.g. snowmelt and temperature. It repeats the values of an annual cycle for the entire period and thus accounts for the drought definition using a constant threshold level (*Q*90), which implies that the basic seasonal "readiness" of a region for drought is higher during the low flow season.

Based on these considerations, the logistic regression was carried out with the following independent variables X_i:

- For each of the eight CP groups:
  short-term influence (daily occurrence);
  mid-term influence (30-day lag: frequency and centre of gravity); and
  long-term influence (half-year lag: frequency and centre of gravity).
- Average Pardé-Regime for each cluster.

RESULTS

An example of the time series of streamflow drought events in the individual catchments of cluster 4 and the resulting *RDI* are represented in Fig. 3(a) and (b). The simultaneous CP-group occurrences (Fig. 3(c)) and their lag frequencies (Fig. 3(d) and (e)) illustrate the influence of atmospheric circulation on the drought response of the cluster as it was then included in the logistic regression. During the drought years of 1990 and 1991, the CP group II (high pressure, dry weather) was more frequent and persistent than usual, especially in spring before the strong 1991

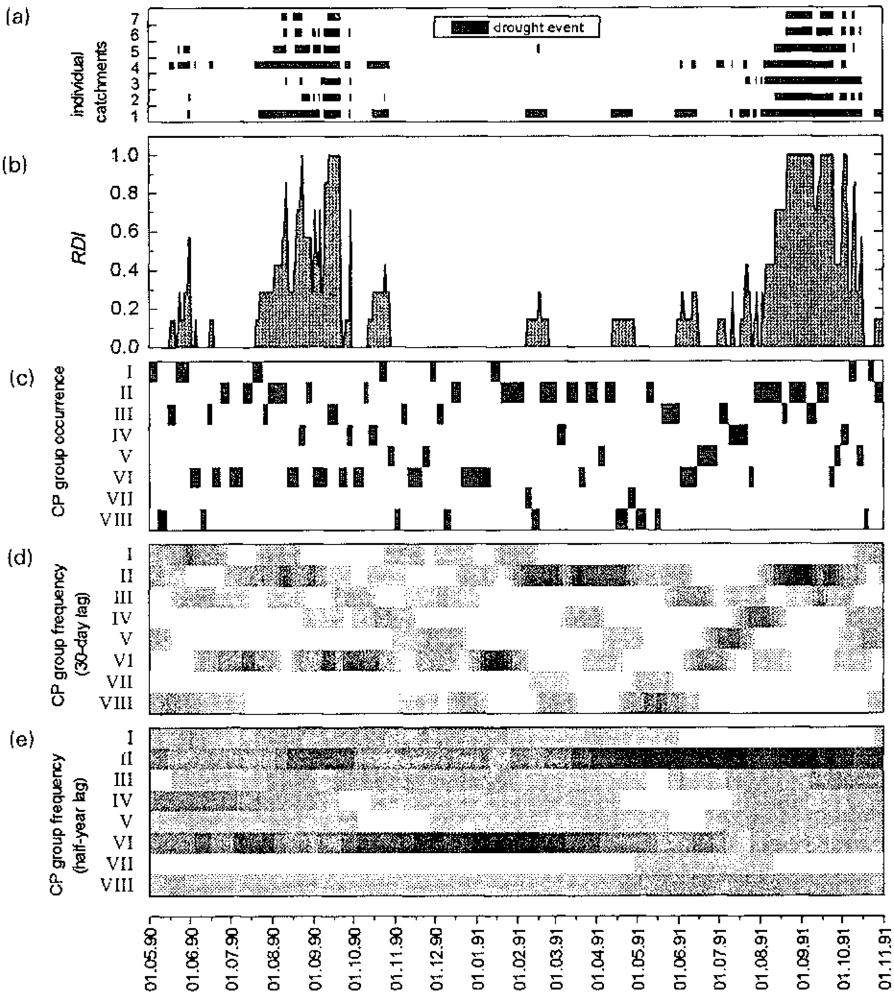

Fig. 3 The 1990 and 1991 droughts: (a) drought spells in individual catchments of C4, (b) Regional Drought Index (*RDI*), (c) daily CP-group occurrence, (d) CP-group frequency during 30-day moving time window, and (e) CP-group frequency during half-year moving time window (grey scales for (d) and (e) are relative: the darker the shade, the greater the frequency).

summer drought. The low pressure group VIII was less frequent compared to non-drought years and during the 1991 drought it was completely missing. Rainfall of cyclones coming from the Atlantic Ocean (group VI) caused most of the interruptions or terminations of drought events in the C4 catchments. This group seems to be most effective in the northern and western mountain ranges. The eastern clusters do not show this instantaneous response.

For C1 to C4, the logistic regression model 1 simulated more than 70% and model 2 still simulated more than 60% of the event days of the studied time period correctly. The results for the eastern clusters were poorer, which underlines the influence of the westerly airflow in central Europe decreasing towards the east. Yearly fluctuations of the number of event days were successfully calculated by the logistic

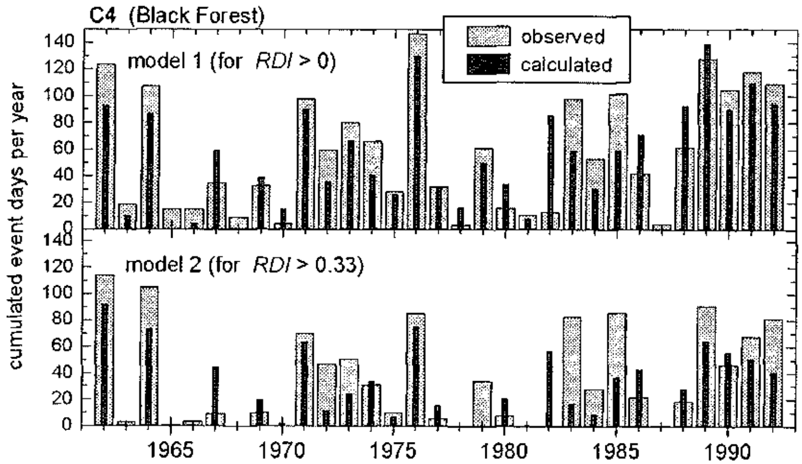

Fig. 4 Comparison of observed and modelled event days (cumulated) per year for C4.

regression model (Fig. 4). The absolute values for years with a large number of events were generally underestimated. The best relative estimates, however, were achieved for the most severe drought years (e.g. 1976). Within this first application, the relatively short time series did not allow data splitting for validation. However, further investigations will be carried out in the future.

The partial correlations of the many independent variables were assessed in a qualitative sense. Among the 41 variables, around 30–35 were typically included in the two different models for each cluster. Short- to mid-term CP-group influences were strongest in the western highland regions. This behaviour corresponds to the known high streamflow variability in these hard-rock dominated steep basins. On the contrary, the response of the pre-alpine basins with their large aquifers of unconsolidated till sediments more strongly depends on long-term meteorological history. For future application of the model, a reduction of the independent variables should be considered in order to facilitate these comparisons.

CONCLUSION

The results demonstrate a considerable influence of synoptic meteorology on streamflow drought and reveal important information on the relationship of CP occurrence and drought. Most important for the development of streamflow drought in southern Germany is the persistence of high pressure and anticyclonic circulation patterns. The relevant time lag strongly varies with regional storage related characteristics. The capability of the logistic regression model has to be further evaluated on additional data. However, the study shows a promising forecasting potential for the statistical linkage of atmospheric circulation patterns and regional drought.

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