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Probabilistic dependence between streamflow and hydroclimatic variables and the possible linkages to large-scale atmospheric circulation: A case study in Baden-Württemberg, Southwest Germany

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ABSTRACT

This study presents an investigation of probabilistic relationships between streamflow and hydroclimatic variables (including precipitation, temperature and soil moisture) and the potential links to large-scale atmospheric circulation over Baden-Württemberg, Southwest Germany. First, the joint dependence between seasonal streamflow and hydroclimatic variables was established by using copulas. On the basis of the joint dependence structure, we estimated the probabilities of hydrological droughts and prolonged high-streamflow events conditioned upon two different scenarios (high and low) of hydroclimatic variables for various seasons over the study area. The results indicate that both precipitation and soil moisture are positively related to the streamflow variation in Baden-Württemberg for each season and strongly impact the likelihoods of hydrological droughts and high-streamflow events. Temperature tends to have less impact on the streamflow variation, and an inverse connection between streamflow and temperature is found in spring and summer. Then, the connections between streamflow variability and large-scale atmospheric circulation in summer and winter were explored by using composite analysis. Although the atmospheric circulation patterns vary in each season, it can be found that in summer high streamflow anomalies over Baden-Württemberg are related to a cyclonic activity over central Europe while low streamflow anomalies are linked to anticyclonic patterns over western Ireland. The high streamflow anomalies in winter are strongly impacted by the westerlies that play an important role in favoring warm and moist airstreams from the Atlantic Ocean towards the study area, while an opposite atmospheric pattern is found for the years with low streamflow anomalies. The presented probabilistic methodology could also be applied in other regions worldwide.

1. Introduction

Climatic variables such as precipitation and air temperature have been widely recognized as key parameters in the hydrological cycle. Also, soil moisture affects the process of precipitation transformation into infiltration and streamflow and thus largely determines the streamflow behavior and variability (Aubert et al., 2003). Understanding the linkages between hydroclimatic variables (e.g., precipitation, air temperature, and soil moisture) and streamflow is significant for water resources planning and adapting appropriate practices to deal with the drought and flood risk under extreme conditions. An improved knowledge about these relationships may also assist the further development of hydrological modeling. In the past decades, numerous studies have focused on investigating the relationships between the variability in streamflow and changes in the hydroclimatic driving phenomena over different parts of the world. On the one hand, some researchers focused on employing deterministic correlation coefficient and linear statistical approaches such as multiple linear regressions to examine the influence of regional hydroclimatic variables on streamflow and the potential links between them (Brocca et al., 2008; Cayan et al., 1993; Cunderlik and Burn, 2004; Ficklin et al., 2009; Kletti and Stefan, 1997; Penna et al., 2011; Stewart et al., 2005). On the other hand, many scholars investigated the hydrological response to climate and environment variability based on conceptual or physically-based hydrological models, and also assessed the sensitivity of the streamflow to changes in the hydroclimatic drivers (Hamlet and Lettenmaier, 2007; Jha et al., 2004; Menzel et al., 2006, Zehe et al., 2010; Zhang et al., 2011). However, few studies have focused on building up the joint probabilistic dependence between streamflow and hydroclimatic factors and identifying the conditional likelihoods of prolonged high-

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streamflow events and hydrological drought under varying hydroclimatic scenarios, particularly regarding the seasonal variation. This probability-based information would be of great value for water resources planning and prevention. To identify the joint probabilistic dependence between streamflow and hydroclimatic variables, copulas could be an ideal tool. The main advantages of copulas include allowing the dependence to be constructed independently from the marginal distributions, and modeling different marginal distributions without any transformations (Genest and Favre, 2007). During the past decade, copulas have gained popularity and there are increasing applications of copulas in multivariate hydrological modeling, For instance, in the field of flood frequency analysis, single variable analysis has been widely used in the past while it has the problem in handling the multivariate stochastic flood characteristics such as volume, peak, and duration of the flood hydrograph (Bobée and Rasmussen, 1994). Copulas provide an effective solution to model the joint dependence structure of uncertain multiple flood characteristics (Reddy and Ganguli, 2012). In order to improve the estimation of design flood hydrograph, Requena et al. (2013) introduced a bivariate copula model to simulate the joint distribution of flood peak and volume and to obtain the return periods linked to the risk of dam overtopping. Rainfall intensity-duration-frequency (IDF) curves are very important in floodplain management and urban drainage design. However, in order to model joint distributions of rainfall variables including intensity, depth and duration, many previous studies assumed these variables are independent, have the same marginal distribution (usually assumed to be normal distribution or transformed to normal distribution). Singh and Zhang (2007) developed copula-based IDF curves by relaxing such assumptions. In addition, copulas offer an effective tool in other hydrological applications such as return periods of drought events, hydrological prediction, drought identification and geostatistical interpolation (Bárdossy and Li, 2008; Genest and Favre, 2007; Liu et al., 2015a; Madadgar and Moradkhani, 2013; Reddy and Ganguli, 2012; Salvadori and De Michele, 2004; Song and Singh, 2010; Tong et al., 2015; Zhang and Singh, 2007; Wang et al., 2012).

Large-scale atmospheric circulation is known to strongly affect precipitation variability and thus the changes in streamflow. There have been many studies focusing on the changes in atmospheric dynamics and their links to regional hydrological processes and extreme flow events in Europe. Jacobeit et al. (2003) detected the connections between flood events and atmospheric circulation patterns for the past 500 years in central Europe. They described how some specific atmospheric circulation modes (as a dynamic factor) significantly influence the incidence of flood events. Bardossy and Filiz (2005) identified the flood-producing atmospheric circulation patterns (CPs) by means of large-scale pressure fields over some *meso*-scale catchments in France and Spain. Bouwer et al. (2006) quantitatively assessed the impact of variation in atmospheric circulation on the changes in winter streamflow over northwestern Europe. They reported that the frequency of the westerlies over Europe could be a useful reference for investigating climate change impacts on streamflow in northwest Europe. Ionita et al. (2012) examined the streamflow in the Rhine River and the links to large-scale climate anomaly patterns in spring and autumn using composite analysis, and concluded that the variability of the atmospheric circulation pattern significantly affects the precipitation fluctuations and Rhine streamflow variability in both seasons.

The current study focuses on investigating how streamflow and hydroclimatic factors are coupled in Baden-Württemberg, Southwest Germany, particularly focusing on the likelihoods of prolonged high-streamflow events and hydrological drought under different hydroclimatic conditions. Several previous studies have provided valuable knowledge about the linear connections (e.g., the correlation analysis) between the streamflow variability and hydroclimatic changes over some specific regions or basins in Baden-Württemberg (e.g., Huang et al., 2015; Schröter et al., 2015; Warrach-Sagi et al., 2008). However, little previous work has been done to probabilistic relationships between streamflow and hydroclimatic forcings and the likelihoods of hydrological droughts and high-streamflow events under different hydroclimatic conditions in Baden-Württemberg. The current study attempts to quantify the seasonal probabilistic dependence structure between streamflow and hydroclimatic factors including precipitation, temperature and soil moisture over Baden-Württemberg by using copulas. The established dependence structure allows the evaluation of the likelihoods of hydrological droughts and prolonged high-streamflow events conditioned on different hydroclimatic scenarios. Moreover, large scale atmospheric circulation imposes an important impact on the precipitation over this area and thus strongly affects the hydrological extremes. This study also seeks to explore the possible connections between streamflow in Baden-Württemberg and large-scale atmospheric circulation. This analysis may provide additional information to understand the streamflow variability based on prior knowledge from varying atmospheric circulation patterns.

2. Methodology

The proposed framework in the study consists of three components. The first one involves building up joint dependence structure of streamflow and hydroclimatic variables based on copula; the second part is the conditional simulations and the final part aims to evaluate the probabilistic difference with given conditions. Additionally, the empirical orthogonal function (EOF) analysis was used here to identify dominant spatial modes of streamflow over the study area.

2.1. Probabilistic measures of the dependence between streamflow and different hydroclimatic variables

A copula is simply described as a joint distribution function from multiple variables (Laux et al., 2011; Madadgar and Moradkhani, 2013; Sklar, 1959). Based on Sklar's theorem (Sklar, 1959), a bivariate distribution $F_{X,Y}(x, y)$ for variables X and Y can be expressed by a copula that satisfies:

$$F(x, y) = C(F_X(x), F_Y(y)) = C(u_1, u_2) \tag{1}$$

C is called a copula which is the joint cumulative distribution function (CDF), and its form reflects the joint dependence structure ($u_1 = F_X(x)$ and $u_2 = F_Y(y)$).

Modeling the joint dependence structure requires a well-fitted marginal distribution of each variable. To determine the best-fit distribution of the variables, four common theoretical probability distributions which are commonly used in hydroclimatology were compared: normal, gamma, Weibull, and lognormal (Kao and Govindaraju, 2010; Khedun et al., 2014; Madadgar et al., 2014). The parameters of each distribution were estimated by the maximum likelihood method (Gyasi-Agyei, 2013). To determine the appropriateness of the theoretical distributions and discriminate between them, the chi-squared goodness-of-fit was employed (Madadgar and Moradkhani, 2013; Massey, 1951). This test returns the p value, which should be greater than the significance level (5%) to accept the null hypothesis. The most appropriate distribution was determined by the smallest statistics (the corresponding p value should be greater than the significance level as well) from the chi-squared test.

After obtaining the best-fitted marginal distributions, an approximate bivariate copula is expected to join the margins and construct the joint dependence. In this study, several commonly-used copulas were considered such as Gaussian, Clayton, Gumbel, Frank, and Joe. The details of these copulas used in the current study are found in Liu et al. (2015b).

To select the copula that best models the dependence of the given data, a parametric bootstrapping goodness-of-fit test was used (Genest and Rémillard, 2008; Madadgar and Moradkhani, 2013). The goodness-of-fit test is called the Cramér-von Mises test which computes the Cramér-von Mises statistic S_n as a measure of the distance between the