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Transitional properties of droughts and related impacts of climate indices in the Pearl River basin, China

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SUMMARY

Drought is the natural hazard poorly understood so far due to various mechanisms behind. Moreover, disastrous effects of drought on human society necessitate accurate forecasting of drought behaviors. In this case, to improve forecasting of drought in the Pearl River basin, a trivariate copula model has been developed and used to include the El Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Indian Ocean Dipole (IOD) and Pacific Decadal Oscillation (PDO) into model structure of Markov chain. The Standardized Precipitation Evapotranspiration Index (SPEI) has been used to monitor the drought in this study. Comparison with the preliminary correlation analysis between each month climate index and SPEI series indicated that the trivariate copula performs satisfactorily well in evaluation of influences of climate indices on the transition probabilities of drought. It is considered that the region with the negative vertical velocity is dominated by more precipitation and vice versa. Moreover, field patterns of 500 hPa vertical velocity anomalies related to each climate index have further corroborated the influences of climate indices on the drought behaviors. Besides, the mean extreme drought durations under different conditions of each climate index have also been investigated in this study. Results indicated that the mean extreme drought duration tends to be longer in the western part of the Pearl River basin during positive phase of ENSO while tends to be shorter during the positive phase of NAO and vice versa; in the central part of the Pearl River basin, the mean extreme drought duration tends to be shorter during the positive phase of ENSO, NAO and PDO while tends to be longer during the positive episode of IOD, and vice versa; in the eastern part of the Pearl River basin, the mean extreme drought duration tends to be shorter during the positive episode of ENSO and PDO, and vice versa. This study sheds new light on transitional behaviors of droughts as a result of influences from climate indices.

1. Introduction

In recent decades, given changing climatic and documented increases in extreme climate events, human concerns has grown worldwide pertaining to the fact that droughts have the potential to intensify in frequency, severity and duration (Peterson et al., 2013; Wilhite et al., 2014). As a prolonged water deficit event, drought has a devastating effect on agriculture, energy production, urban water supply, public health, ecosystem, and the economy. It is estimated that the USA economic losses caused by droughts are as high as 6–8 billion dollars each year, being far more than other meteorological disasters (Wilhite, 2000). However, unlike other extreme climate events such as floods, earthquakes, hurricanes, the evolution of drought is slow, then an effective mitigation of the most adverse drought impacts is possible by capitalizing on the delay between the onset of drought and the moment when its consequences are perceived by the water supply systems or the end-users (Bonaccorso et al., 2015).

Accurate forecasting of drought plays a significant role in developing appropriate policies to mitigate the drought hazards, and the ability to accurately forecast the onset, persistence and cessation of drought conditions is fundamental to the development and implementation of efficient mitigation strategies. In recent years, many

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statistical and non-statistical techniques have been proposed for the forecasting of drought (Bonaccorso et al., 2015; Madadgar and Moradkhani, 2013; Yuan et al., 2013). Based on the Climate Forecast System, version 2 (CFSv2) and the Variable Infiltration Capacity (VIC) land surface model, Yuan et al. (2013) have established a seasonal hydrologic forecasting system for Africa. The 2012 drought was one of the most extensive drought events in the United States, resulting in the economic loss over 12 billion USD, AghaKouchak (2014) found that this drought was predictable several months in advance based on the persistence property of accumulated soil moisture. In addition, with the copula function to model the autocorrelated streamflow or hydrologic drought, a multivariate probabilistic approach to perform drought forecasting within a Bayesian framework has been proposed by Madadgar and Moradkhani (2013) that a future drought status can be estimated given the earlier drought conditions.

Regardless of the specific methodology, Bonaccorso et al. (2015) stated that a distinction can be made with reference to the different objectives of the drought forecasting. This current study focuses on determining transition probabilities from a given current drought class to another one in the future, and this has been largely evaluated by the Markov chain models (Bonaccorso et al., 2015; Cancelliere et al., 2007; Madadgar and Moradkhani, 2013; Paulo and Pereira, 2007; Sanusi et al., 2015). In our previous studies (Chen et al., 2015), with the drought monitored by the Standardized Precipitation Evapotranspiration Index (SPEI) with the time scale of 3 months, the drought characteristics of the Pearl River basin has been analyzed using the Markov chain. Due to the limited sample size of observed transitions among different drought classes, it has been found that the lack of observed transitions in some cases would lead to the misleading conclusion that such transitions have zero occurrence probability when the transition probability matrix was estimated by the maximum likelihood method (Cancelliere et al., 2007; Chen et al., 2015). To avoid these drawbacks of the maximum likelihood method, a method to theoretically calculate the transition probability matrix based on the bivariate copula function has been introduced in our previous paper (Chen et al., 2015).

Despite such efforts, the forecasting of drought is still a tough task. Recently, much attention has been attached to forecasting of drought behaviors using climate indices as main predictors, such as the El Niño Southern Oscillation (ENSO) (Chen et al., 2013a) and North Atlantic Oscillation (NAO) (Bonaccorso et al., 2015). With advances in the field of synoptic climatology, it has been found that ocean–atmosphere interactions are not chaotic or random, and influences of global climatic indices on weather and hydrological extremes have been drawing increasing concerns (Cai et al., 2011; Dai, 2013; Moore et al., 2013; Xiao et al., 2015; Zhang et al., 2014). Located in the south China, the climate of the Pearl River basin is dominated by the East Asian Monsoon, it has also been well studied that the East Asian Monsoon has been significantly influenced by the ENSO, NAO, Indian Ocean Dipole (IOD) and Pacific Decadal Oscillation (PDO) (Chen et al., 2013b; Linderholm et al., 2011; Xiao et al., 2015; Yuan et al., 2008; Zhang et al., 2014). In our previous studies, the possible influences of ENSO, NAO, IOD and PDO on the seasonal precipitation in the Yangtze River basin (Xiao et al., 2015) and the Poyang Lake basin (Zhang et al., 2014) have been analyzed. In Sicily (Italy), with NAO as exogenous input variable, Bonaccorso et al. (2015) found that the probabilistic models of Markov chain perform better for short and middle term forecasting of drought transition probabilities. Then it is also necessary to encompass the ENSO, NAO, IOD and PDO into the models structure of Markov chain to improve the drought forecasting in the Pearl River basin. However, such reports have not been available so far which to some degree limit human mitigation to droughts in the Pearl River basin.

As an extension of our previous study (Chen et al., 2015), a trivariate copula has been developed and used to model the dependence between two consecutive monthly SPEI and each climate index, and then the transition probability matrix under different conditions of each climate index can be calculated, details of the calculation can be referred to Section 3. With respect to the case when the climate index is neglected, the enhancement in forecasting drought transition probabilities has been quantified in the study. Furthermore, based on the NCAR/NCEP reanalysis dataset, the 850 hPa wind anomalies and 500 hPa vertical velocity anomalies related to each climate index have been investigated to verify the results, and these will be important to further understand the possible geophysical processes linking the teleconnections of each climate index to monthly drought in the Pearl River basin. In addition, the paper is organized as follows: introduction of study region and data is presented in Section 2; methods of analysis are depicted in Section 3; and results and discussion thereof are described in Section 4, which is followed by Section 5 as the conclusion of this study.

2. Study region and data

Located in the south China, the Pearl River (102°14′E–115°53′E; 21°31′N–26°49′N) is the second largest river in terms of the water volume and the third largest river in terms of the drainage basin area in China. The Pearl River basin is 4.573×10^5 km^2 in drainage area with three major tributaries: the West River, the North River and the East River (Fig. 1). As located in the tropical and subtropical climate zones, the annual mean temperature of the Pearl River basin ranges from 14 °C to 22 °C, with long-term annual average precipitation of 1525.1 mm. The distribution of precipitation is uneven during the year, and precipitation from April to September accounts for 80% of the annual total (Chen et al., 2015; Zhang et al., 2012).

Obtained from the National Meteorological Information Center of the China Meteorological Administration, daily precipitation data and 2 m air temperature (maximum temperature and minimum temperature) data were analyzed, covering a period of 1959–2013 at 46 meteorological stations across the Pearl River basin. Detailed information of the meteorological data analyzed in this study can be referred to Chen et al. (2015). Locations of these meteorological stations are shown in Fig. 1. In addition, as the climate across the Pearl River basin is complicated and diverse, the Pearl River basin has been subdivided into three sub-regions, i.e. the western, central and eastern part of the Pearl River basin (Fig. 1). Same as the data used in our previous study (Xiao et al., 2015), the ENSO are indicated by Niño 3.4 indices in the study, derived from sea surface temperature anomaly estimates in the Niño 3.4 region (5°N–5°S, 120°W–170°W), and details of the sources for the ENSO, NAO, IOD and PDO can be referred to Xiao et al. (2015).

3. Methodology

3.1. Standardized Precipitation Evapotranspiration Index (SPEI)

As an extension of the widely used Standardized Precipitation Index (SPI), the SPEI has been proposed by Vicente-Serrano et al. (2010) to analyze the drought, which can capture the effect of increased temperatures on water demand. The SPEI is designed to take into account both precipitation and potential evapotranspiration (PET) in determining drought. PET is the amount of evaporation and transpiration that would occur if a sufficient water were available. The SPEI with the time scale of 3 months has been calculated in the Pearl River basin to analyze the drought (Chen et al.,