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Drought analysis according to shifting of climate zones to arid climate zone over Asia monsoon region

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S U M M A R Y

When a humid region is affected by arid climate, significant changes in drought characteristics occur due to imbalance of water budget. In this study, change in drought characteristics according to shift of different climates i.e. tropical, warm temperate, cold and polar to Arid Climate (SAC) was analyzed over the Asia monsoon region. Climate zones and the SAC regions were identified by applying the Köppen climate classification on hydro-meteorological data for the period of 1963–2006. The analysis of hydro-meteorological parameters revealed that the annual precipitation and runoff in the SAC regions appeared to decrease about 12.1% and 27.3%, respectively, while annual average temperature increased about 0.5 °C. Standardized runoff index (SRI) was calculated using model-driven runoff data. The trend and change point analyses of SRI were performed to evaluate the changes in drought characteristics (frequency, duration, severity) before and after shifting of the different climates to arid climate. The results revealed strong decreasing trend of SRI and hence intensified drought conditions for the SAC regions. A change point year of drought occurred about 3–5 years earlier than the shifting time of the SAC region. Frequency and duration of droughts in the SAC regions were observed to increase about 9.2 and 1.5 months, respectively, and drought severity index intensified to about −0.15. It can be concluded that analysis of shifting to arid climate zones should be considered together with changes in drought characteristics, because the drought characteristics and changing arid climate zones are closely related to each other.

1. Introduction

The recent global warming has caused extreme changes in water resources (IPCC, 2007). In particular, the increase in arid climate region leading to water scarcity has been more pronounced around the world. Fraedrich et al. (2001) reported that the arid climate regions increased over the globe, while the tundra climate regions decreased during the last 15 years in 20th century. Beck et al. (2006) reported that arid climate regions extended around the world in the late 20th century when global warming progressed rapidly. Gerstengarbe and Werner (2009) showed a significant increase in the steppe and subtropical climate zones in Europe and explained the correlation between climate extensions and NAO (North Atlantic Oscillation) index. Ma et al. (2005) analyzed the decadal variability of climate zones in China and indicated that the arid regions have expanded to southeast direction in northern China.

On the other hand, drought is another important issue around the world due to climate change. Dai et al. (2004) reported that the global warming has increased the risk of drought based on the analysis of PDSI (Palmer Drought Severity Index) during the past observation period. Sheffield and Wood (2008a) analyzed the changes in continental-scale drought characteristics by using a soil moisture-based drought index. They showed the increase in drought areas in Africa and Northeastern Asia regions. Global warming is recognized as a major factor for aridity and drought and its impacts are projected to increase in the future (Sheffield and Wood, 2008b; Rubel and Kottek, 2010; Feng et al., 2011). These findings highlight the necessity of countermeasures to reduce the damage.

In general, aridity defined by the moisture shortage is a kind of climate phenomenon in an average sense (Agnew and Anderson, 1992). Drought is a phenomenon caused by water shortage which occurs due to below normal precipitation condition for a specific period of time. Both humid and arid regions experience droughts (Maliva and Missimer, 2012). Aridification is associated with increasing temperature trend and decreasing trends of precipitation, runoff and soil moisture (Smakhtin and Schipper, 2008; Some'e et al., 2012; Ahani et al., 2013). SAC may have significant impact on drought features. In previous studies, the trend and variation analysis of meteorological and hydrological components

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have been mainly focused. Although analysis of drought characteristics was performed in arid regions (Wander et al., 2010), SAC was not considered.

The purpose of this study was to analyze the changes in drought for the SAC regions in the Asia monsoon region. For this study, meteorological and hydrological data were collected over the Asian monsoon region. The SAC regions were selected by using dry-wet classification function. The drought index was estimated, and the several changes i.e. trend, frequency and changing time in drought were analyzed in the regions.

2. Methodology

2.1. Classification of arid climate

Aridity Index (AI) and Climatic Classification (CC) have generally been used to determine the aridity in a region. AI is estimated through comparison of precipitation and potential evapotranspiration. It can quantitatively estimate the degree of aridity as well as the determination of arid region. Several aridity indices have been developed (Thornthwaite, 1948; UNESCO, 1979) and the arid conditions over continental or global scale were presented (Meigs, 1953; Kassas, 1995). The CC was suggested in order to find similarities of climate variables over a region and to organize the mean spatial climate characteristics. The typical one is a Köppen CC developed by a plant physiologist in 1900 (Wang and Overland, 2004; Kottek et al., 2006; Peel et al., 2007). Although, this method cannot describe the aridity conditions quantitatively, it has some advantages such as the ability to clearly define the boundary between humid and arid climate zones and easy computation as described in the literature (Kalovova et al., 2002; Rubel and Kottek, 2010). Many authors have used the Köppen CC to determine the climate zones and to analyze the climate shifts (Fraedrich et al., 2001; Beck et al., 2006). The Köppen CC has been modified by various authors (Bailey, 1962; Trewartha and Horn, 1980; Triantafyllou and Tsonis, 1994), but the original Köppen CC (hereafter referred to as Köppen–Geiger CC) is still most frequently used classification (Kottek et al., 2006). In this study, the Köppen–Geiger CC was used to select the SAC regions over the Asian monsoon region.

Köppen–Geiger CC comprises a total of 31 climate zones according to climate boundary condition (Rubel and Kottek, 2010). In this study, 5 major climate zones, namely equatorial climate (A), arid climate (B), warm temperate climate (C), snow climate (D) and polar climate (E) were used because the drought changes corresponding to SAC can be thoroughly analyzed from these 5 types of climate classification. Table 1 shows the description of the Köppen–Geiger CC.

Köppen grouped the world climate as A, C, D and E climate zones, and as B climate zone according to moisture availability required for plant growth. The dryness threshold (P_{th}) in Eqs. 1–3 is suggested to account for water losses by evaporation and transpiration. The arid climate zone B is determined when the annual precipitation (P_{ann}) is less than the $10P_{th}$ as shown in Table 1, while the rest of the climate zones A, C, D and E are determined when the P_{ann} is greater than the $10P_{th}$. To identify A, C, D or E climate zones which are mutually exclusive, the B climate zone determined from annual mean temperature (T_{ann}) and precipitation should be identified at first. In this study, the value of $P_{ann} - 10P_{th}$ is named as D_{AC} (Discriminator of Arid Climate).

Table 1
Classification of major climate zones by Köppen method.

Type	Description	Criterion
A	Tropical climates	Tmin ⩾ +18 °C
B	Arid climates	Pann < $10P_{th}$
C	Warm temperate climates	−3 °C < Tmin < +18 °C
D	Cold climates	Tmin ⩽ −3 °C
E	Polar climates	Tmax < +10 °C

P_{th}: water losses by evaporation and transpiration (mm), Tmax: mean temperature of the warmest months (°C), Tmin: mean temperature of the coldest months (°C), Pann: annual precipitation (mm/year).

$$P_{th} = 2(T_{ann}) + 28 \text{ (if at least 2/3 of the annual precipitation occurs in summer, mm)} \quad (1)$$

$$P_{th} = 2(T_{ann}) \quad \text{(if at least 2/3 of the annual precipitation occurs in winter, mm)} \quad (2)$$

$$P_{th} = 2(T_{ann}) + 14 \text{ (otherwise)} \quad (3)$$

For SAC analysis, the required minimum data period should be selected. Fraedrich et al. (2001) investigated this requirement for 15 climate types during the period of 1901–1995 and proposed at least 15 years data as the minimum requirement. In this study, the data period for SAC computation is fixed to minimum requirement of 15 years due to limitation of available data length. The SAC regions are determined by computing the climate zones for each year by using moving window of 15 years over the whole data period. For example, the climate zones in 1977 and 1978 are computed using the data of 1963–1977 and 1964–1978, respectively. Similarly, classifications are obtained for the period of 30 years (1977–2006).

2.2. Drought index

Drought is classified as meteorological, hydrological and agriculture drought in accordance with analysis perspectives. Many drought indices are suggested to quantify the drought conditions and characteristics. The typical drought indices include Standardized Precipitation Index (SPI; Mckee et al., 1993), Palmer Drought Severity Index (PDSI; Palmer, 1965), Standardized Runoff Index (SRI; Shukla and Wood, 2008), Surface Water Supply Index (SWSI; Shafer and Dezman, 1982) and Crop Moisture Index (CMI; Palmer, 1968).

The Köppen arid climate is determined through the comparison of atmospheric precipitation and ground water loss. Therefore, SAC has a close relationship with changes of hydrological cycle. For drought analysis, selection of the appropriate drought index is necessary. In this study, we selected the SRI to analyze the drought according to SAC. The computation method of SRI is the same as that of SPI. However, SRI is different from the SPI in a sense that the SRI was developed to synthetically consider ground moisture contents such as surface runoff, subsurface runoff and snowmelt, while the SPI uses precipitation only (Awan and Bae, 2015; Wang et al., 2011). The drought duration in this study is selected to 12 months, because the Köppen 5 major climate types are computed by annual average temperature and precipitation. The cumulative probability is estimated from the selected probability distribution that appropriately considers low flow behaviors in a region. In previous studies, the Log-normal and Gamma distributions were used for American regions (Shukla and Wood, 2008; Jung and Chang, 2012). For the selection of appropriate distribution, eight distributions such as 2- and 3-parameter log-normal (LN2, LN3), Gamma (GAM), Pearson type-3 (PE3), Log-Pearson type-3 (LP3), Gumbel (GUM), General Extreme Value (GEV) and Wakeby (WAK) were considered and L-moment method was applied to determine the parameters of probability distribution (Hosking, 1990). The appropriate probability distribution was selected through goodness-of-fit test (the Kolmogorov–Smirnov test and Chi-square test). Drought index was calculated through