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Research paper

A modified soil water deficit index (MSWDI) for agricultural drought monitoring: Case study of Songnen Plain, China

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ABSTRACT

Available soil water in the root zone is an essential component of the water balance process since it greatly affects the crop water uptake and crop growth. In this study, a modified soil water deficit index (MSWDI) was established on the basis of the concept of readily available water (RAW), with the accumulated effect considered. This modified index was applied in six agro-meteorological stations in Songnen Plain of China to monitor the agricultural drought. The results showed that: 1) The MSWDI showed similar spatial and temporal agricultural drought patterns as its inherent indices, such as the soil water deficit (SWD), soil moisture deficit index (SMDI) and atmospheric water deficit (AWD), but exhibited a delay between atmospheric and soil water processes; 2) The MSWDI has a better correlation with the crop yield than its inherent indices. For example, its overall correlation coefficient is about 0.6 with the crop yields among six study stations and −0.7 for the number of droughts, while their corresponding values are 0.5 and −0.6, 0.5 and −0.6, and 0.3 and −0.4 for SMDI, SWD and AWD, respectively; 3) The MSWDI could also identify a slightly higher number of reported drought events during the 2000–2012 in comparison with SMDI, SWD and AWD, although it also over-predicts the number of drought events same as other indices. It mainly comes from the uncertainty of reported drought events. The proposed index can be used for agricultural drought monitoring and provides a useful tool for agricultural meteorology and water resource management.

1. Introduction

Drought is of global concern for the society since it has significant impacts on water quantity and quality and greatly influences the food, water, and energy security, but it originates as a local problem (Mishra et al., 2015). In particular, among the three commonly recognized categories of drought, i.e., meteorological, hydrological and agricultural drought, the agricultural drought has a more direct and immediate impact on the society (Mishra and Singh, 2010). Agricultural drought can be considered as the result of a shortage of precipitation over a particular time scale, leading to a soil moisture deficit that limits the water availability for crops to such an extent that the crop yields are reduced (Panu and Sharma, 2002; Wilhite et al., 2011; Sepulcre et al., 2012). Besides, there are strong linkages between soil moisture and atmosphere as well as crops, which make the soil moisture squarely in the center of the spectrum of drought indicators, and therefore it is reasonable to consider soil moisture as a suitable approach for agricultural drought monitoring (Ochsner et al., 2013).

A range of indicators have been used to detect and monitor agricultural drought, and most of early indices are based on long-term atmospheric data (e.g. rainfall, temperature) or a water balance equation based on meteorological variables (Martínez-Fernández et al., 2015). For example, the concept of evapotranspiration (ET) as a measure of water demand leads to the development of the Palmer Drought Severity Index (PDSI) (Palmer, 1965), and the Crop Moisture Index (CMI) (Palmer, 1968) is based on a subset of the calculations required for the PDSI, which is primarily a meteorological drought index. The standardized precipitation index (SPI) at the 1–3 month scale can also be used to monitor agricultural drought (McKee et al., 1993). The Atmospheric water deficit (AWD) was proposed by Purcell et al. (2003), which is used to assess drought for summer crops based on long-term weather data. Narasimhan and Srinivasan (2005) used the Evapotranspiration Deficit Index (ETDI)

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for agricultural drought monitoring based on the concept of the water stress from the reference crop ET and the actual ET, both of which are outputs of the Soil and Water Assessment Tool (SWAT) model.

In recent years, most studies of agricultural indices have focused on the soil moisture based on observations and estimation from remote sensing and/or modeling. For example, Narasimhan and Srinivasan (2005) monitored the agricultural drought with the Soil Moisture Deficit Index (SMDI) on the basis of the soil moisture simulated with the SWAT. The Agricultural Reference Index for Drought (ARID) is based on a reference crop, which uses a simple soil water balance equation (Woli et al., 2012). Torres et al. (2013) developed a drought probability assessment method using long-term measurements of soil water deficits (SWD). Ceppi et al. (2014) used meteorological forecasts and hydrological modeling to simulate the soil moisture as a component of a. real-time agricultural drought forecasting system. Keshavarz et al. (2014) introduced the Soil Wetness Deficit Index, which is calculated from the land surface temperature data and the MODIS Normalized Difference Vegetation Index (NDVI) data. The Soil Water Deficit Index (SWDI) used observations as an approach for monitoring agricultural drought (Keshavarz et al., 2014). The Standardized Soil Moisture Index (SSMI) is derived from an assimilated crop model with AMSR-E soil moisture and MODIS-LAI data (Mishra et al., 2015). Scaini et al. (2015) used SMOS-derived soil moisture anomalies for agricultural drought monitoring.

Most of current agricultural drought indices associated with the soil moisture deficit directly used the soil water content or indirectly referred to the concept of available soil moisture, i.e. the water content beyond the wilting point. Although the water is theoretically available until the wilting point, the crop water uptake is reduced well before the wilting point is reached (Allen et al., 1998). Besides, the plant water stress is more strongly related to the relative amount of plant-available water in the soil than the absolute amount of soil moisture (Allen et al., 1998; Martínez-Fernández et al., 2015). Moreover, developing a reliable drought index for agriculture requires proper consideration of the vegetation type, crop growth and root development, soil properties and antecedent soil moisture condition (Kleidon and Heimann, 1998; Zeng et al., 1998; Li et al., 2001; Narasimhan and Srinivasan, 2005). But only a few agricultural drought indices have taken into account the soil water availability relative to the crop water extraction. The SWD index assesses the drought probability with the relative amount of plant-available water (Torres et al., 2013), but it doesn't take into account the prior soil moisture condition, which is an important drought monitoring factor.

In the present work, a modified soil water deficit index (MSWDI) was developed as a drought index on the bais of the soil moisture calculated with a crop growth model. This new index is based previous SWD index (Torres et al., 2013) and is modified through considering the antecedent soil water deficit condition. This index was tested and verified using several reference indices, field observation of drought events, and crop yields in six local-scale agricultural sites in Songnen Plain, China. The primary aim of this study is to verify and assess the applicability of this newly proposed index in agricultural drought monitoring to improve agricultural water management.

2. Materials and method

2.1. Study sites location

Songnen Plain (121°20′–128°25′ E and 43°36′–49° 30′ N) is one of the most important food production areas of China, which consists of a piedmont area in the west part, a central low plain, and an elevated plain in the east part. The mean annual precipitation ranges from 500 to 600 mm in the east elevated plain to 300–450 mm in the west piedmont area (Chen et al., 2011). Being controlled by the East Asian monsoon, the precipitation in Songnen Plain changes dramatically during an annual cycle but mainly concentrates in the flood season (June to September) (Wang and Ripley, 1997), and only 10–20% of the precipitation occurs in the spring (Li et al., 2006). Pan evaporation is between 700 and 1000 mm, more than 40% of which occurs in the spring (Zhang et al., 2011). The droughts with long duration and large areas cause great losses in the agricultural production and economic development in this area.

2.2. Data

The meteorological data during 2000–2012 were provided by the China Meteorological Administration (CMA), which is responsible for monitoring, collecting, compiling and releasing hydro-meteorological data in China (Zhao et al., 2012) (Table 1). The meteorological data used in this study include the precipitation, maximum air temperature, minimum air temperature, relative humidity, sunshine hours, and wind speed data, which are recorded according to the standard methods of the World Meteorological Organization's guide to the Global Observing System and the CMA's Technical Regulations on Weather Observations (Fu et al., 2013). These data were quality-controlled and their consistencies were tested before being released by the CMA (http://cdc.cma.gov.cn).

The agricultural drought records were provided by the CMA (http://cdc.cma.gov.cn), which included the affected crops, occurrence time, severity, durations, afflicted areas, and ratios during 2000–2012. The crop growth and relative soil moisture data were also provided by the CMA (Huang and Li, 2010), which contained the records of crops, crop yield, growth periods, heights of crops, the conditions of growth, density of crops, and relative soil moisture for the 10-, 20-, 50-, 70-, and 100-cm layers. The relative soil moisture data were measured generally 10-day interval during the growing season without irrigation. In order to match this study, the relative soil moisture data was converted to volumetric soil

Table 1
Main data description.

Category	Variable	Type	Length of observations
Meteorological data	Irradiation	$(kJ\,m^{-2}\,d^{-1})$	2000–2012
	Minimum temperature	degrees Celsius	2000–2012
	Maximum temperature	degrees Celsius	2000–2012
	Vapour pressure	kPa	2000–2012
	Mean wind speed	$m\,s^{-1}$	2000–2012
	Precipitation	mm/d	2000–2012
	Duration of sunshine	hour/day	2000–2012
Soil date	Soil water content	10,20,50,70,100 cm layer(m^3/m^3)	2000–2012(Changling,1993–1999)
Crop date	Growth stage	date	2000–2012
	Grain yield	yearly	2002–2012
Drought record date	Agricultural Drought Disaster	10days	2000–2012