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Spatio-temporal analysis of drought in a typical plain region based on the soil moisture anomaly percentage index

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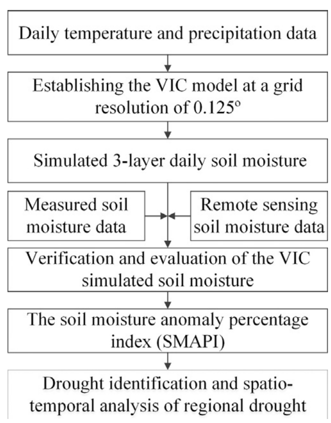
HIGHLIGHTS

- The VIC model was built at a resolution of 0.125° × 0.125° in a typical plain region.
- The 56-year simulated 3-layer daily soil moisture database was reconstructed.
- SMAPI is a powerful index for spatio-temporal analysis of regional drought.

GRAPHICAL ABSTRACT



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ABSTRACT

Drought strongly affects the agricultural economy, most severely in plain regions, with prosperous agricultural development, which suffer huge economic losses. An effective index is required to describe the process of drought initiation, development, and alleviation, and soil moisture is a vital variable with respect to agricultural drought as a comprehensive variable. In this study, Jiangsu province was selected as a typical plain region, the VIC (Variable Infiltration Capacity) model was used to simulate soil moisture at a resolution of 0.125° × 0.125°, and the soil moisture anomaly percentage index (SMAPI) was established for drought identification and investigation of drought spatio-temporal characteristics between 1956 and 2011. The results show that the VIC model built in our study is feasible, and the simulated 3-layer daily soil moisture database can be used in drought studies as an alternative to measured soil moisture. The droughts in the northern part of the province are more severe than those in the southern part, and Xuzhou is the most frequently affected city. There are no strong trends of drought duration in 13 cities of Jiangsu province. Among the 13 cities, drought intensity decreases as drought duration increases for the same drought area, and drought intensity decreases with drought area for the same drought duration. The methods used here in our study to build the VIC model for plain regions that lack closed basin hydrologic data may be helpful for further studies of VIC, and the regional analysis of drought can provide a powerful reference for regional drought prevention and resistance in Jiangsu province.

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1. Introduction

Drought, one of the most hazardous natural disasters in the world, has complex impacts on agriculture, the environment, and socio-economic development (Moeletsi and Walker, 2012; Patel et al., 2012; Du et al., 2013). Due to frequent droughts, plain regions, categorized by prosperous agricultural and economic development, suffer significantly. The Middle-Lower Yangtze Plain, the most important agricultural production base and the one of the most advanced economic areas in China, is one of the areas most severely affected by drought (Jia and Pan, 2013). And the winter-spring drought of 2011 was the most severe drought in nearly 60 years, the long duration and large area of the drought caused extensive socio-economic losses. The drought led to a 3,705,000 hm^2 crop damage area, of which the crop failure area was as large as 167,000 hm^2; the direct monetary loss amounted to 14.94 billion RMB. Moreover, the following droughts-floods abrupt alternation exacerbated the losses. Thus, effective evaluation of drought variability and an understanding of drought regularity are of practical significance for promoting agricultural production in plain regions as well as ensuring food security and sustainable regional development.

The spatial and temporal distribution of drought and drought monitoring remain key issues in drought research, and relevant research in plain regions has been carried out across the world. Establishing an effective drought index is vital for drought research, and meteorological drought indexes are the most widely used. As meteorological data is easy to obtain, in-situ data are widely used to establish drought indexes for drought monitoring and drought characteristic analysis. Based on the Palmer Drought Severity Index (PDSI), Todd et al. (2013) analyzed droughts in the southeastern plains of the UK, and the Standardized Precipitation Index (SPI) was used to analyze drought characteristics of the eastern fertile alluvial plain region of Turkey (Karabulut, 2015). The spatial and temporal distribution of droughts in the Huang-Huai-Hai plain was analyzed based on the Standardized Precipitation Evapotranspiration Index (SPEI) (Wang et al., 2015), and extreme droughts were studied in Qinghai by He et al. (2016).

For data-poor or non-data regions, the database can be simulated by models, and the simulated data can be used for drought analysis after verification as an alternative to measured data (Mao et al., 2015; Wanders and Van Lanen, 2015; Ma et al., 2016). With the development of satellite remote sensing technology, relevant drought studies have been carried out using remote sensing data (precipitation, temperature, etc.) (De Jesús et al., 2016; Dorjsuren et al., 2016; Hoek et al., 2016; Xu et al., 2016). However, the meteorological indexes mainly consider the influence of precipitation on drought over a period of time, so they have certain limitations reflecting the spatio-temporal variation of droughts, and the research time scale tends to be large (usually on the monthly scale). In order to improve the display of spatial and temporal drought variability, the drought indexes based on soil moisture have been gradually developed, considering the effect of underlying surface characteristics on regional drought. Soil moisture is a comprehensive variable of various climatic, vegetation, and soil properties, and it plays a crucial regulatory role in the water supply to crops during random precipitation events (Kim, 2010; Li and Ma, 2015; Wu and Kinter, 2009; Wu et al., 2012). A drought index based on soil moisture (usually on a daily scale), can not only reflect the influence of land-atmosphere interactions on the spatial and temporal evolution of drought, but also recognize the phenomenon of alternating drought-flood in plain regions.

However, the applications of a drought index based on soil moisture content are limited, because it is difficult to measure soil water content, especially in-situ (Wu et al., 2007; Cristi et al., 2016). Remote sensing data is an alternative to in-situ soil moisture on large scales due to improved spatial coverage, and is considered to be fast and economic (Scaini et al., 2014). As part of the development of satellite remote sensing technology, several microwave-based soil moisture products have been generated over recent decades, such as the Advanced Scatterometer (ASCAT) soil moisture product (Wagner et al., 2013), the Soil Moisture and Ocean Salinity (SMOS) satellite (Kerr et al., 2001), the Climate Change Initiative (CCI) soil moisture project (Hollmann et al., 2013), etc. These datasets are important reference materials for drought research. However, current remote sensing databases can only give soil moisture in the thin, upper layers due to the influence of vegetation and other factors (Wu et al., 2011), so the soil moisture of the entire soil profile cannot be directly retrieved. Furthermore, the record lengths of the databases are still relatively short (Wang et al., 2011), and the early data records usually show a high proportion of missing data. Application of remote sensing soil moisture data is therefore limited.

To obtain large-scale and long series soil moisture data for historical agricultural drought research, the Variable Infiltration Capacity (VIC) model, which has been successfully applied in China (Hao et al., 2015; Niu et al., 2015; Ma et al., 2016; Wang et al., 2016), can be used to simulate soil moisture over a large area. The advantage is that VIC can simulate daily soil moisture, so that the daily drought index can be established to study drought occurrence and intensity at different spatial and temporal scales. Furthermore, more importantly, the VIC model can provide reliable soil moisture status information, as different vegetation types and soil properties are considered when determining the impact of hydrological processes. Wu et al. (2007) performed preliminary simulations of soil moisture at a resolution of 30 km all over China and achieved good results using the VIC model based on long-term meteorological data. Based on a previous study, in our study, Jiangsu province in the Yangtze River Plain was selected as the typical study region, and soil moisture simulated by the VIC model was used for drought analysis. The specific aims of this study are:

(1) Construct the VIC model by combining two sets of gridding formulas (Lu et al., 2010, 2013) for parameter calibration in the plain region with insufficient hydrological data at a higher resolution of 0.125° × 0.125°.
(2) Validate and evaluate the simulated soil moisture using measured soil moisture and Climate Change Initiative (CCI) soil moisture data.
(3) Establish the daily Soil Moisture Anomaly Percentage Index (SMAPI) to identify historical droughts in the districts of Jiangsu.
(4) Analyze the spatial and temporal characteristics of droughts and the relationships among drought duration, area, and severity.

2. Data and methods

2.1. Data

2.1.1. The VIC model and simulated soil moisture data

Jiangsu is an eastern coastal province of China (116.3–121.95°E, 30.75–35.33°N), extending from north to south. Jiangsu province has an area of 102,600 km^2, and plains account for over 70% of the whole province.

This study used daily temperature and precipitation data from 113 rain gauge stations from 1956 to 2011. The data were derived from the China Meteorological Data Sharing Service System and Jiangsu Province Hydrology and Water Resources Investigation Bureau. According to the Impact of Climate Change on Jiangsu Water Resources and Strategy project, soil moisture was simulated based on a 24 h time step, and the water balance was calculated at a resolution of 0.125° × 0.125° in the VIC model. The station data were estimated on a 0.125° grid using the inverse distance weighting method. The distribution of grids and stations in Jiangsu province is shown in Fig. 1.

2.1.2. Validation data for simulated soil moisture

In this study, we used both remote sensing soil moisture data from the Climate Change Initiative (CCI) and measured soil moisture to validate the simulated soil moisture.