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# Combination of multi-sensor remote sensing data for drought monitoring over Southwest China

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ABSTRACT

Drought is one of the most frequent climate-related disasters occurring in Southwest China, where the occurrence of drought is complex because of the varied landforms, climates and vegetation types. To monitor the comprehensive information of drought from meteorological to vegetation aspects, this paper intended to propose the optimized meteorological drought index (OMDI) and the optimized vegetation drought index (OVDI) from multi-source satellite data to monitor drought in three bio-climate regions of Southwest China. The OMDI and OVDI were integrated with parameters such as precipitation, temperature, soil moisture and vegetation information, which were derived from Tropical Rainfall Measuring Mission (TRMM), Moderate Resolution Imaging Spectroradiometer Land Surface Temperature (MODIS LST), AMSR-E Soil Moisture (AMSR-E SM), the soil moisture product of China Land Soil Moisture Assimilation System (CLSMAS), and MODIS Normalized Difference Vegetation Index (MODIS NDVI), respectively. Different sources of satellite data for one parameter were compared with in situ drought indices in order to select the best data source to derive the OMDI and OVDI. The Constrained Optimization method was adopted to determine the optimal weights of each satellite-based index generating combined drought indices. The result showed that the highest positive correlation and lowest root mean square error (RMSE) between the OMDI and 1-month standardized precipitation evapotranspiration index (SPEI-1) was found in three regions of Southwest China, suggesting that the OMDI was a good index in monitoring meteorological drought; in contrast, the OVDI was best correlated to 3-month SPEI (SPEI-3), and had similar trend with soil relative water content (RWC) in temporal scale, suggesting it a potential indicator of agricultural drought. The spatial patterns of OMDI and OVDI along with the comparisons of SPEI-1 and SPEI-3 for different months in one year or one month in different years showed significantly varied drought locations and areas, demonstrating regional and seasonal fluctuations, and suggesting that drought in Southwest China should be monitored in seasonal and regional level, and more fine distinctions of seasons and regions need to be considered in the future studies of this area.



## Introduction

Drought is considered to be the most complex but least understood of all natural hazards, affecting more people than any other hazard (Hagman, 1984). While the damages of drought are well documented, a restriction of proper definition of drought has always been a challenge for researchers (Tate and Gustard, 2000; Quiring and Papakryiakou, 2003; Łabędzki, 2007; Zhang et al., 2010; Zhang et al., 2014). According to Wilhite and Glantz (1985), droughts have been classified into four categories, i.e., meteorological, agricultural, hydrological and social economic droughts. Since social economic drought is even more difficult to define and monitor than other categories because of its dependence upon complex social economic conditions, the other three drought categories are more related to water deficit. Meteorological drought is a precipitation departure from atmospheric evaporation, agricultural drought is related to soil moisture deficit, and hydrological drought is related to the deficit of surface and subsurface water (Heim, 2002).

In the last two decades, many drought indices were formulated by integrating weather variables such as precipitation,

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evapotranspiration and temperature into a single number, and a series of drought indices were developed on the basis of different drought categories (Kangas and Brown, 2007; Zargar et al., 2011). The most commonly used drought indices include Palmer drought severity index (PDSI) (Palmer, 1965), standardized precipitation index (SPI) (McKee et al., 1993; Edwards, 1997; Hayes et al., 1999), and standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010), which are calculated by in situ meteorological data. The SPI and SPEI can be obtained for flexible time scales while PDSI can only be achieved for one time period. However, as a regional event, drought has difficulty in monitoring spatially by these in situ indices though they can be estimated using gridded data, whose accuracy and level of spatial detail are subject to the functions of the density and the distribution of the station network. Since the remote sensing data are capable of capturing spatial details and have been developed in recent years (Kogan, 1997), they can be used to detect the onset of drought, its duration and magnitude on regional scales (Thiruvengadachari and Gopalkrishna, 1993; Kogan, 1995a,b; 1997).

A series of indices derived from remote sensing data have been used to detect the drought events on a regional scale, the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974; Yang et al., 1998), Vegetation Condition Index (VCI) (Kogan, 1995a,b), Temperature Condition Index (TCI) (Bhuiyan et al., 2006; Jain et al., 2009) and soil moisture drought index (Hollinger et al., 1993) have been widely used. The NDVI has been the most widely used drought index which reflects the vegetation conditions (Farrar et al., 1994; Yang et al., 1998; Ji and Peters, 2003), a series of other indices reflecting vegetation information were developed such as VCI, Standardized Vegetation Index (SVI) (Peters et al., 2002), and Vegetation Health Index (VHI) (Kogan, 1995a,b). Similarly, the TCI and Soil Moisture Condition Index (SMCI) were also introduced to monitor drought occurrence (Zhang and Jia, 2013). Moreover, the VHI which combines the VCI and TCI was developed to assess vegetation drought stressed by temperature (Kogan, 1995a). With the use of Tropical Rainfall Measuring Mission (TRMM) remote sensing data in recent years, integrated drought indices were developed to monitor meteorological and agricultural drought conditions by combining the single remote sensing indices, e.g., TCI, VCI, SMCI and TRMM Precipitation Condition Index (PCI). The Scaled Drought Condition Index (SDCI) was designed with three indices TCI, VCI and PCI with different percentage to monitor agricultural drought (Rhee et al., 2010) in the North and South Carolina of the United States, and then with the same method by weighing the percentage of each unique remote sensing index, Microwave Integrated Drought Index (MIDI) was developed with multi-sensor microwave indices (TCI, SMCI and PCI) and was used to monitor short-term especially meteorological drought distribution in North China (Zhang and Jia, 2013). The Synthesized Drought Index (SDI) defined as a principal component of VCI, TCI and PCI was used to monitor the comprehensive drought that occurred in Shandong province of China (Du et al., 2012).

This study intended to develop the optimized drought indices (ODIs, i.e., OMDI and OVDI) from multi-sensor remote sensing data for monitoring meteorological and vegetation droughts, and the constrained optimization method was adopted to construct the optimal weights for ODIs in Southwest China. The ODIs were integrated with parameters such as precipitation, temperature, soil moisture and vegetation information as derived from TRMM, Moderate Resolution Imaging Spectroradiometer land surface temperature (MODIS LST), MODIS NDVI, and soil moisture selected from three products, i.e., AMSR-E soil moisture (AMSR-E SM) products from the official product from National Snow and Ice Data Center (NSIDC) of US and from both of the Vrije Universiteit Amsterdam and NASA Goddard Space Flight Center (VUA-NASA), and product from China Land Soil Moisture Assimilation System (CLSMAS). While the integrated indices (e.g., SDCI, MIDI and SDI) were developed by Rhee et al. (2010), Du et al. (2012) and Zhang and Jia (2013), and were compared with station-based indices SPI or PDSI to assess the applicability and reliability in monitoring drought over regional scales. Since the recently developed SPEI takes both precipitation and temperature into account through potential evapotranspiration formulas (e.g., Thornthwaite method), it has the advantage of combining multi-scalar character with the capacity to include the effects of temperature variability on drought assessment, which is better than SPI in calculating water balance mathematically and is better than PDSI in multiscalar analysis (Vicente-Serrano et al., 2010; Seibert and Apel, 2012). Thus, this study used SPEI as one of the in situ indices. And different sources of remote sensing data for one parameter were compared with in situ drought indices SPI and SPEI from multitime scales in order to select the best data source to derive the ODIs.

The objectives of this study were to (1) establish optimized meteorological and vegetation drought indices (OMDI and OVDI) from multi-sensor remote sensing data for monitoring drought of complex landforms; (2) assess the data reliability of soil moisture products from different satellite sources for establishing ODIs; (3) utilize the constrained optimization method in generating the ODIs and to assess their performance of them by both of the two in situ drought indices SPI and SPEI; and (4) investigate the drought patterns by ODIs and SPEI of multi-temporal scale in Southwest China over space and time.

## Study area and data

### *Study area*

The study area is situated in southwest of China, located between 97.34°–112.06° N and 21.13°–34.32° E (Fig. 1), covering an area of $1.42 \times 10^6$ km$^2$.

The elevation varies largely with three obvious steps, i.e., high elevation from 4000 to 6000 m, mid-elevation from 1000 to 4000 m and low elevation less than 1000 m (Fig. 1a), from which three major regions A, B and C were classified over the study area. Various landforms cause greatly different vegetation types (Fig. 1b), precipitation (Fig. 1c), and temperature (Fig. 1d) conditions from the northwest to the southeast of the study area. The major vegetation types for regions A, B and C are mixed forest, grassland and cropland, respectively. Region A and C belong to subtropical monsoon climate zone, while Region B belongs to alpine-cold climate. The annual average differences for precipitation and temperature among the three regions are as high as 2000 mm and 24 °C approximately. In the last 30 years, increasing population has added to the growing demand for water and other natural resources in Southwest China. Drought has become a common natural disaster in Southwest China in recent years, bringing significant water shortages, economic losses and adverse social consequences (Su et al., 2014). Severe drought events have occurred in the summer of 2006, autumn of 2009 and spring of 2010 in the recent decades (Li et al., 2009; Li et al., 2012; Wang and Chen, 2012), causing great agricultural loss and severe drinking water shortage.

### *In situ reference data and drought indices*

Monthly precipitation data and mean temperature data from 1981 to 2010 were obtained from China Meteorological Data Service (http://data.cma.gov.cn) over the study area. Only those meteorological stations having long term climate data available from 1981 with no missing data were selected. Thus data for 30 stations in Region A, 21 stations in Region B and 21 stations in Region