Remote Sensing of Environment 142 (2014) 1–8

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Assessment of soil water deficit for the middle reaches of Yarlung-Zangbo River from optical and passive microwave images

Lei Zhong [a,b,c,*], Yaoming Ma [b], Yunfei Fu [a], Xiao Pan [a], Wei Hu [d], Zhongbo Su [c], Mhd. Suhyb Salama [c], Lu Feng [a]

[a] Laboratory of Atmosphere Observation and Water Cycle, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China
[b] Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China
[c] Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands
[d] Fundamental Surveying and Mapping Information Center of Anhui Province, Hefei, China

ARTICLE INFO

Article history:
Received 8 April 2013
Received in revised form 3 November 2013
Accepted 9 November 2013
Available online 5 December 2013

Keywords:
Surface Energy Balance System
Soil moisture
The Tibetan Plateau

ABSTRACT

The middle reaches of Yarlung-Zangbo River (YZR) and its two tributaries (Lhasa River and Nianchu River) is a main agricultural region in central Tibet Autonomous Region. Soil water deficit (SWD) estimation has significant relevance to local crop growth monitoring, crop yield assessment and disaster monitoring. It also has great theoretical importance for understanding the local energy and water balance status. In this paper, AVHRR and MODIS data on 14 April 2003, 16 October 2003 under nearly clear weather conditions are selected as the spring and autumn cases. Land surface parameters, such as land surface temperature, surface albedo, Normalized Difference Vegetation Index, and emissivity, have been derived from different algorithms for AVHRR and MODIS data. In combination with meteorological data, the soil water deficit index is determined by applying Surface Energy Balance System. The R square values between SWDI and AMSR-E soil moisture are ranging from 0.457 to 0.607, with spring SWD being much more severe than that in autumn. The limited river runoff (less than 5% of the annual total) is the dominant factor for spring SWD. This study also reveals that the derived spring SWD from AVHRR and MODIS data is quite different on the same day. This phenomenon is caused by different satellite overpass times which influence the melting frozen soil. This also confirms that the soil moisture may have diurnal variations. The spatial variations of SWD conditions in the middle reaches of YZR and its two tributaries have been clearly identified.

1. Introduction

Globally, soil water deficit (SWD) is considered to be one of the world's most common phenomena. Especially in recent years, water shortage is becoming more serious with increasing social and economic development (Jang, 2009). Under the background of climate change (Donohue, Roderick, McVicar, & Farquhar, 2013; McVicar et al., 2012; Sun, Roderick, & Farquhar, 2012), water scarcity has become one of the most urgent problems that needs to be recognized and solved (Rosegrant, Ringler, & Zhu, 2009; Van Loon & Van Lanen, 2013).

SWD is the difference between field capacity and the actual soil water content in the root zone. In other words, SWD is often caused by a reduction in the availability of soil water (Wanjura & Upchurch, 2000) inadequate to meet the evapotranspiration demand (Padhi, Misra, & Payero, 2012). Actually, SWD is directly linked to evapotranspiration. While drought is a complex phenomenon whose severity is specific regionally due to local energy and water balance status (Shahabfar, Ghulam, & Eitzinger, 2012). It is a natural hazard, caused by large-scale climatic variability, and cannot be prevented by local water management (Van Loon & Van Lanen, 2013). It refers to an anomaly when compared to a long-term climatology. Four major types of drought are broadly defined and agreed upon in the scientific literature (McVicar & Jupp, 1998). They are meteorological drought, agricultural drought, hydrologic drought and socioeconomic drought. Some linkages exist between SWD and drought. Both drought and SWD are all related to energy transfer and water cycle processes. More or less SWD usually can be found in drought-prone regions. However, the converse is not necessarily true.

The severity of SWD can be assessed with meteorological based indices (e.g., the standardized precipitation index) (Su et al., 2003) or other methods, such as lysimeter and the neutron probe detection method. However, all these indexes are based on the in-situ measurements, and hence represent a 'point' in the landscape. A lot of manpower, material and financial resources need to be invested to get the limited point-level SWD information. It is impossible to acquire local or regional SWD situations through the above methods.

SWD is directly linked to evapotranspiration. In recent decades, a wide variety of models have been developed using satellite data to

---

* Corresponding author at: Laboratory of Atmosphere Observation and Water Cycle, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China.

E-mail address: zhonglei@ustc.edu.cn (L. Zhong).

0034-4257/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.rse.2013.11.008

estimate evapotranspiration (Ma, Hafeez, Ishikawa, & Ma, 2013), such as the Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen, Menenti, Feddes, & Holtslang, 1998), the Surface Energy Balance Index (SEBI; Menenti & Choudhury, 1993), and the Simplified Surface Energy Balance Index (S-SEBI; Roerink, Su, & Menenti, 2000). Although these models have successfully assessed the surface heat fluxes and monitored the SWD on a small scale, they usually lose strength for larger scales at which the underlying surface conditions are no longer homogenous any more. Overall, various remote sensing models are built on the premise of certain conditions. The above existing methods often lose their applicability in the Qinghai-Tibet Plateau area because of the complex terrain and characteristic environmental conditions there.

The development of Surface Energy Balance System (SEBS) (Su, 2002; Su et al., 2003) provides a possibility for the SWD monitoring in the study area. For the specific region of YZR and its two tributaries, previous studies focused on the analysis of the land–atmosphere interaction based on the in-situ measurements (e.g., Song et al., 2011; You, Kang, Wu, & Yan, 2007). As for satellite remote sensing, many studies focused on the retrieval algorithms of land surface parameters (e.g., Ma, Ma, Zhong, Chu, & Bianba, 2010; Ma, Zhong, Wang, & Su, 2012; Zhong, Ma, Ma, Chu, & Bianba, 2011; Zhong et al., 2012). Hence, it's necessary to know the applicability of soil water deficit index (SWDI) derived from energy balance aspect for the YZR and its two tributaries. By monitoring surface SWD conditions by remote sensing promotes a quantitative understanding of the regional energy and water cycle and provides technical supports for the scientific management and rational use of local water resources.

The purpose of this study is to verify the validity of SEBS-derived SWDI and reveal its spatio-temporal pattern in the study area. Two questions are answered through this study. Firstly, how to identify the validity of SWDI estimated by SEBS? Soil moisture derived from AMSR-E is used to make a comparison with SWDI. Secondly, what's the spatio-temporal pattern of SWDI in YZR and its two tributaries? AVHRR and MODIS data with similar spatial resolution are introduced to reveal the patterns. These two questions form the basis for the structure presented in the Methods (Section 4), Results (Section 5) and Discussion (Section 6) sections below.

2. Study site

Referred to as the "roof of the world" and the "third pole of the earth" (Qiu, 2008), the Tibetan Plateau (TP, also known as the Qinghai–Xizang Plateau) is well known both for its high elevation (McVicar & Körner, 2013) and unique geographical features (Ma et al., 2006, 2011; Zhong et al., 2012). The middle reaches of Yarlung-Zangbo River (YZR) and its two tributaries (Lhasa River and Nianchu River) is a main agricultural region in central Tibet Autonomous Region producing 56.8% of the TP agricultural production (Wei, Yang, & Dong, 2004). It is not only a climate-sensitive area, but also an ecologically fragile region in TP. SWD monitoring has significant meaning for local crop growth monitoring, crop yield assessment and disaster monitoring.

The study area is comprised of the YZR, Lhasa River (LR) and Nianchu River (NR) watersheds (Fig. 1a, b). YZR is the highest major river in the world (You et al., 2007). The river flows from west to east through the South Tibet Valley (3–5 km wide). The middle reaches of YZR and its two tributaries cover 60,000 km^2 which is 5% of Tibet Autonomous Region. However, it contributes 10% of the cultivated area and has 50% population in Tibet. It is a central agricultural region and natural water vapor corridor for warm and wet air flow from the Indian Ocean (Zheng & Li, 1999). Climatologically the precipitation decreases from east to west and vegetation type follows this gradient (Fig. 1c, d). The typical rooting depth of vegetation in the study area is about 0–10 cm (He, Shi, & Xu, 2009; Li & Koike, 2003).

3. Materials

3.1. NOAA-16 AVHRR and Terra MODIS data

AVHRR and Terra MODIS radiance data are used to retrieve land surface parameters, such as LST, surface albedo, NDVI, Leaf Area Index (LAI) and emissivity. All these derived parameters are inputs for SEBS. The images taken on 14 April and 16 October 2003 are selected to represent spring and autumn, respectively.

3.2. AMSR-E data

Volumetric soil moisture derived from Advanced Microwave Scanning Radiometer (AMSR-E) is used to validate the SWDI results from SEBS. The AMSR-E on the Aqua Earth observation satellite was launched in May 2002. The sensor is 12 channels (six frequencies), with 4 bands relevant to soil moisture retrieval. Orbit characteristics are somewhat similar to its predecessor, Scanning Multichannel Microwave Radiometer, although the AMSR-E swath width is nearly twice as wide at 1445 km (Owe, de Jeu, & Holmes, 2008). The data represent the volumetric soil moisture (of a soil layer about 5 cm deep) retrieved using the Land Parameter Retrieval Model (Owe et al., 2008) from AMSR-E C band data. The data has a spatial resolution of 0.25°.

3.3. In-situ meteorological data

Nine meteorological stations are located in the study area (Fig. 1a). The conventional hourly observational items, such as wind speed, air temperature, humidity, air pressure, solar radiation, and sunshine hours, are used in the study. The wind speed is measured at 10 m while other variables are recorded at 2 m above the land surface. To adjust wind speed data obtained from instruments placed at elevations other than the standard height of 2 m, a logarithmic wind speed profile may be used (Allen, Pereira, Raes, & Smith, 1998; Su, 2002).

$$U_2 = Uz * 4.87/[\ln(67.8 * z - 5.42)] \tag{1}$$

where U_2 is the wind speed at 2 m above ground surface, Uz is the measured wind speed at z m above ground surface, and z is the height of measurement.

The sunshine hours are used to calculate the average daily net radiation by using a simplification of the equation presented by Allen et al. (1998). The net radiation was estimated by the following equation.

$$R_n = (1-\alpha) \cdot R_{swd} + \varepsilon \cdot R_{lwd} - \varepsilon \cdot \sigma \cdot T_0^4 \tag{2}$$

where α is the albedo, ε is the emissivity of the surface, σ is the Stefan–Boltzmann constant, T_0 is the land surface temperature, R_{swd} is the downward solar radiation which can be calculated by the Iqbal (1983), and R_{lwd} is the downward longwave radiation which can be calculated as $R_{lwd} = \varepsilon_a \sigma T_a^4$.

4. Methods

4.1. Comparison from soil moisture perspective

As the study area is located at mid-latitudes where the daily AMSR-E swath does not fully cover (Ashcroft & Wentz, 2003), the products (both ascending and descending) retrieved in one month have been averaged. These products have basic filters applied that mask freezing conditions. The AMSR-E soil moisture have been validated with in-situ soil moisture measurements in the TP and the soil moisture measurements are in good agreement with the meteorological data and consistent in space and time (Dente, Vekerdy, Wen, & Su, 2012). This means that the AMSR-E soil moisture can be used to make a comparison with SWD.