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A practical approach for deriving all-weather soil moisture content using combined satellite and meteorological data

Pei Leng [a], Zhao-Liang Li [a,b,*], Si-Bo Duan [a], Mao-Fang Gao [a], Hong-Yuan Huo [a]

[a] Key Laboratory of Agricultural Remote Sensing, Ministry of Agriculture/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

[b] State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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ABSTRACT

Soil moisture has long been recognized as one of the essential variables in the water cycle and energy budget between Earth's surface and atmosphere. The present study develops a practical approach for deriving all-weather soil moisture using combined satellite images and gridded meteorological products. In this approach, soil moisture over the Moderate Resolution Imaging Spectroradiometer (MODIS) clear-sky pixels are estimated from the Vegetation Index/Temperature (VIT) trapezoid scheme in which theoretical dry and wet edges were determined pixel to pixel by China Meteorological Administration Land Data Assimilation System (CLDAS) meteorological products, including air temperature, solar radiation, wind speed and specific humidity. For cloudy pixels, soil moisture values are derived by the calculation of surface and aerodynamic resistances from wind speed. The approach is capable of filling the soil moisture gaps over remaining cloudy pixels by traditional optical/thermal infrared methods, allowing for a spatially complete soil moisture map over large areas. Evaluation over agricultural fields indicates that the proposed approach can produce an overall generally reasonable distribution of all-weather soil moisture. An acceptable accuracy between the estimated all-weather soil moisture and in-situ measurements at different depths could be found with an Root Mean Square Error (RMSE) varying from 0.067 m^3/m^3 to 0.079 m^3/m^3 and a slight bias ranging from 0.004 m^3/m^3 to -0.011 m^3/m^3. The proposed approach reveals significant potential to derive all-weather soil moisture using currently available satellite images and meteorological products at a regional or global scale in future developments.

1. Introduction

Due to the ability of controlling the partition of turbulent energy on the Earth's surface into sensible and latent fluxes and the allocation of rainfall into infiltration and runoff, soil moisture has long been recognized as one of the most important surface variables in terrestrial ecosystems, climate and water cycle (Jackson et al., 1996; Seneviratne et al., 2010; Rahimzadeh-Bajgiran et al., 2013; Leng et al., 2014; Hasan et al., 2014; Peng et al., 2016; Wang et al., 2016). Currently, rapid developments of satellite remote sensing technology allow a wealth of algorithms for deriving soil moisture from space data. In particular, at present, several microwave-based soil moisture products can be freely accessed for various applications. For an instance, the soil moisture Climate Change Initiative (CCI) project, led by the European Space Agency (ESA), was started in 2010 and has been dedicated to producing the most complete and most consistent global soil moisture data record based on active and passive microwave sensors (Dorigo et al., 2015). The latest released version (v03.2) of CCI products cover a period of 37 years from 1978 to 2015, which can significantly contribute to a number of studies, such as drought monitoring, precipitation and evapotranspiration over large regions or even at the global scale (Ghulam et al., 2007; Taylor et al., 2012; Li et al., 2013; Duan et al., 2014; Peng et al., 2015; Martínez-Fernández et al., 2016).

Although microwave emissions can penetrate clouds and rain and provide continuous soil moisture products at present, there are at least two critical issues involved in the currently available microwave-based soil moisture products with respect to generat-

* Corresponding author at: Key Laboratory of Agricultural Remote Sensing, Ministry of Agriculture/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China.

E-mail address: lizl@unistra.fr (Z.-L. Li).

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ing all-weather soil moisture products. (1) Microwave signals are most likely to be interrupted by Radio Frequency Interference (RFI), especially over China (Le Vine and Matthaeis, 2014; Zhang et al., 2017). These contaminated pixels will be missing for generating soil moisture products. (2) The algorithms for deriving soil moisture products are limited in several specific conditions, such as the non-convergence of iterative algorithms and situations in which the vegetation water content is over a certain value (Xiao et al., 2016). All these issues will directly lead to significant data gaps in the retrieval of soil moisture, making it difficult for deriving all-weather soil moisture products. Moreover, the coarse spatial resolution (25–50 km) of most currently available microwave-based soil moisture products is insufficient for practical applications at watershed or regional scales, where a spatial resolution of 1–10 km is commonly required for various studies (Crow et al., 2010; Peng et al., 2017). In comparison to the coarse microwave soil moisture products, optical/thermal infrared images typically possess finer spatial resolutions, which can satisfy the requirements for various watershed or regional scale applications. However, optical/thermal infrared observations are more vulnerable when facing adverse weather conditions, leading to the spatially non-continuous problem in the retrieval of all-weather soil moisture, which will greatly limit the applications of soil moisture in various domains. Hence, generating all-weather finer spatial resolution soil moisture datasets is of great significance in the remote sensing community.

To obtain spatially complete satellite products, several gap filling methods have been developed using information from either a temporal or frequency domain (Roerink et al., 2000; Jönsson and Eklundh, 2002; Moody et al., 2005; Liu et al., 2017). However, these currently available gap filling methods for remotely sensed variables such as the Normalized Difference Vegetation Index (NDVI) and the Leaf Area Index (LAI) can feature somewhat less or no explicit physical significance. Because soil moisture features high spatiotemporal heterogeneity and is closely related with environmental factors, such as precipitation, terrain, vegetation and soil properties, it is difficult to fill the soil moisture gaps using simple mathematical interpolations or statistic regressions with only temporal or spatial information implemented in filling the NDVI and LAT gaps. In an earlier study, Moran et al. (1994) proposed a Vegetation Index/Temperature (VIT) trapezoid scheme to obtain soil moisture status over partially vegetated areas using a former developed theory, namely, the Crop Water Stress Index (CWSI) that was originally designed for a fully vegetated condition. Based on the VIT trapezoid framework, soil moisture availability (M_0) and the evapotranspiration fraction for any given pixel within the feature space composed by Land Surface Temperature (LST) and Fractional Vegetation Cover (FVC) or other vegetation index (VI), can be directly determined using only remotely sensed images with theoretical limitation edges determined only by several necessary meteorological inputs in latter developments (Zhang et al., 2008; Long and Singh, 2012; Sun, 2016). This VIT trapezoid scheme provides a feasible approach for deriving soil moisture at a finer spatial resolution from optical/thermal infrared satellite images and with less meteorological data.

Another motivation for deriving all-weather soil moisture from the VIT trapezoid scheme can be attributed to the rapid developments of continental or even global scale meteorological products in the last decade. Currently, several gridded meteorological datasets have been released for public use, such as the 0.125° datasets from the North American Land Data Assimilation System (NLDAS) and the 0.0625° products from the China Meteorological Administration Land Data Assimilation System (CLDAS). Although these meteorological products were primarily designed for global or continental scale data assimilation studies, they provide important inputs for deriving all-weather soil moisture with the aforementioned VIT trapezoid scheme. These high spatial resolution meteorological datasets usually include several necessary elements (e.g., solar radiation, wind speed, air temperature and specific humidity) that are required when determining the theoretical limitation edges using radiation budget and energy balance equations (Moran et al., 1994). Moreover, the gridded meteorological datasets are spatially complete and can provide extra significant information to derive key parameters (e.g., aerodynamic resistance and surface resistance) over the regions where gaps of optical/thermal infrared satellite images occur. These ancillary meteorological data provide an alternative for obtaining soil moisture using other methods over the gap pixels, which is beneficial to deriving all-weather soil moisture on a regional scale.

The objective of this study is to provide a practical approach for deriving finer spatial resolution all-weather soil moisture from combined satellite images and gridded meteorological products on the basis of the VIT trapezoid scheme proposed by Moran et al. (1994). Specifically, the "all-weather" in present study means both the clear-sky and cloudy pixels. Hereinto, a pixel is identified as cloudy pixel if the LST value is not available from the satellite product, whereas a clear-sky pixel is regarded to have valid LST value. In this approach, the optical/thermal infrared information from satellite images is provided to estimate soil moisture with the trapezoid method, in which the gridded meteorological products are used to determine the extreme boundaries of the trapezoid space pixel to pixel. In addition, meteorological products are implemented to calculate the essential parameters for filling gaps where the trapezoid method is not available, aiming to derive all-weather soil moisture data on a regional scale. The proposed approach will be evaluated using ground soil moisture measurements over the study area. Section 2 presents the methods and materials. The results and discussion are presented in Section 3, and conclusions are provided in Section 4.

2. Methods and materials

2.1. VIT trapezoid scheme for estimating soil moisture over clear-sky pixels

In recent decades, a number of studies have been reported to estimate soil moisture and energy fluxes with the VIT trapezoidal/-triangular schemes using satellite imageries at various spatial scales (Petropoulos et al., 2009). One of the most popular forms of the VIT feature space is constituted by LST and VI. Sandholt et al. (2002) firstly proposed a method to estimate soil moisture with the Advanced Very High Resolution Radiometer (AVHRR) data by linking the VIT triangular feature space with an index, namely the Temperature Vegetation Dryness Index (TVDI). Besides, many other scholars have also proposed different forms of VIT feature spaces, such as the LST/albedo feature space (Gómez et al., 2005; Sobrino et al., 2007) and the triangular schemes using the day-night LST difference (or diurnal temperature change) and VI (Chen et al., 2002; Wang et al., 2006; Stisen et al., 2008). In particular, the method reported by Stisen et al. (2008) suggested a nonlinear rather than commonly used linear interpretation of the diurnal temperature change/VI triangular domain for estimating evapotranspiration with the high temporal Meteosat Second Generation (MSG) data. In addition to these, many studies have also proposed the surface-air temperature difference versus VI scatterplot for estimating soil moisture and energy fluxes. In previous studies (Idso et al., 1981; Jackson et al., 1981), the CWSI was used for detecting plant water stress on the basis of the differences between canopy and air temperatures. Specifically, CWSI can only be used over fully vegetated regions and bare soils. Based on the CWSI concept and to overcome the difficulty of obtaining foliage tempera-