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Improving spatial representation of soil moisture by integration of microwave observations and the temperature–vegetation–drought index derived from MODIS products

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ABSTRACT

The microwave observations of land surface soil moisture have been widely used for studying environmental change at large spatial scales. However, the coarse spatial resolution of the products limits their local-scale applications. In this paper, we developed a new method, which integrates the coarse spatial resolution soil moisture derived from microwave sensors and the temperature–vegetation–drought-index (TVDI) derived from the Moderate-resolution Imaging Spectroradiometer (MODIS) products, to spatially downscale soil moisture data from 25-km resolution to 1-km resolution. First, we assessed the quality of the remotely sensed soil moisture by comparing their values with field measured soil moisture at three temporal scales and two spatial scales. Second, we analyzed the robustness of the developed approach namely the PKU method by comparing its performance with the results of three published methods (i.e., the triangle-based method, the Merlin method, and the UCLA method) at the Magqu soil moisture monitoring network located in the northeastern Tibetan grasslands. The modeling results showed that by integrating the contextual information from the relatively fine spatial resolution MODIS products, spatial soil moisture representations were significantly improved. The PKU method produced the most accurate spatially disaggregated soil moisture among the four methods. In conclusion, the PKU method developed in this study is a practical and efficient approach for improving spatial representations of the coarse spatial resolution soil moisture data derived from microwave remote sensors. Within the PKU method, our refined method for estimating the parameters of the dry-edge outperforms the traditional method.

1. Introduction

Land surface soil moisture is a key variable in various hydrological and ecosystem models and for studying climate change, ecosystem dynamics, and crop yields (Chen et al., 2011; Entekhabi et al., 1999; Legates et al., 2011). For example, in hydrology, soil moisture is an important variable for understanding land surface hydrologic processes because it controls the partition of rainfall to subsoil drainage, surface runoff, and evaporation (Han et al., 2012; Mascaro and Vivoni, 2012; Ray et al., 2010). So, understanding the spatial and temporal dynamics of land surface soil moisture is crucial for understanding the role of hydrological cycle in climate systems (i.e., the feedbacks between hydrological cycle and climate change) and a variety of ecological and biogeochemical processes (G. Liu et al., 2012; Oki and Kanae, 2006; Seneviratne et al., 2010). Therefore, accurate monitoring and assessment of land surface soil moisture are increasingly critical for the purpose of analyzing climate variability and change and their impacts on terrestrial ecosystems. Despite the importance of the information about land surface soil moisture, the accurate field measured soil moisture only exist in a limited number of field sites around the world.

Over the past two decades, remotely sensed soil moisture has become much more available while overcoming the limitations of traditional *in situ* point measurements (Anderson and Croft, 2009). In remote sensing of land surface soil moisture, satellite

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images derived from microwave remote sensors have been popular for investigating soil moisture. Microwave remote sensors offer an effective tool to measure land surface soil moisture over various spatial and temporal scales. The fundamental principle of microwave observations of soil moisture is the large contrast in dielectric properties of water and soil. Microwave remote sensors are favored in monitoring soil moisture not only because of their sensitivity to many land surface parameters (e.g., moisture, temperature, and roughness) but also because of their ability to directly measure land surface properties regardless of weather and sunlight conditions (Moran et al., 2004). Microwave observations of land surface soil moisture can be assigned into active (e.g., synthetic aperture radar) and passive (e.g., microwave spectroradiometers) microwave observations. The low temporal frequency and strong sensitivity of active microwave observations to vegetation cover and surface roughness limits their applicability in measuring land surface soil moisture (Hosseini et al., 2015). A major limitation of land surface soil moisture data derived from passive microwave remote sensors is their coarse spatial resolution, which can mask the fine-resolution spatial variability of land surface soil moisture (Kim and Hogue, 2012).

In order to overcome the limitations of passive microwave observations of land surface soil moisture, many methods have been developed to spatially downscale or disaggregate the coarse spatial resolution soil moisture data (Merlin et al., 2008; Kim and Hogue, 2012). The above methods can be assigned into two types: (1) combining passive and active microwave remotely sensed soil moisture data to improve spatial soil moisture representations of the coarse spatial resolution soil moisture data (Liu et al., 2012a, b); (2) integrating the coarse spatial resolution soil moisture data derived from microwave remote sensors and relatively fine spatial resolution optical remote sensing products for deriving the spatial variability of soil moisture at the fine spatial resolution (Chauhan et al., 2003; Choi and Hur, 2012; Piles et al., 2011; Zhao and Li, 2013). Data derived from optical remote sensors can provide detailed contextual information of land surface. In this type of methods, a downscaling factor, which is derived from optical remote sensing products, has been commonly used to represent the spatial variability of soil moisture within coarse spatial resolution remote sensing pixels.

Besides land surface soil moisture data derived from microwave sensors, land surface parameters derived from multispectral optical remote sensing data have been used for estimating land surface soil moisture since the early 1980s (Carlson et al., 1981, 1990, 1995; Leng et al., 2014; Patel et al., 2009; Rahimzadeh-Bajgiran et al., 2012). The normalized difference vegetation index (NDVI) is the most commonly used vegetation index (VI) to analyze the status of vegetation growth, and it is often referred to as a greenness index, which represents vegetation density and chlorophyll content of vegetation rather than the water status of a region. Therefore, in order to monitor water stress, there is a need for a more sensitive indicator than NDVI. Land surface temperature (LST) can be used as a proxy for estimating the status of water stress because the values of LST are high in dry conditions due to the lack of soil moisture. NDVI and LST in combination can provide critical information on the conditions of vegetation and soil moisture (Gillies et al., 1997; Sandholt et al., 2002; Wan et al., 2004). Following this track, many studies have studied the emergence of a triangular or trapezoidal shape when plotting VI against LST (Carlson, 2007). The emergence of the LST/VI triangle is the result of the low sensitivity of LST to soil moisture variations over vegetated areas, and the increased sensitivity of LST to soil moisture variations in areas with bared soil (Sandholt et al., 2002). The focus of these studies has been the analysis of the biophysical properties encapsulated in the LST/VI scatter plot and making associations between these biophysical properties and the estimation of land surface soil moisture (Carlson et al., 1990; Gillies et al., 1997; Petropoulos et al., 2009).

Integrating microwave observations of soil moisture and optical remote sensing products is the most commonly used methods for disaggregating the coarse spatial resolution soil moisture data derived from microwave remote sensors. The LST/VI triangle-based models are the earliest and most commonly used methods. Based on the characteristics of the LST/VI feature space, Chauhan et al. (2003) first integrated passive microwave observations of soil moisture and optical remote sensing products by using a downscaling factor created based on the relatively high spatial resolution optical remote sensing data to improve the spatial variability of soil moisture within coarse spatial resolution pixels. The method was simple to be implemented and used widely since then (Choi and Hur, 2012; Piles et al., 2011; Ray et al., 2010). Merlin et al. (2009, 2010) developed a spatial downscaling method by using a semi-empirical soil evaporative efficiency model to integrate microwave observations of soil moisture and optical remote sensing products, and this model is more biophysically rigorous than the LST/VI triangle-based methods. However, because of requiring many field measured biophysical parameters, the Merlin method is not convenient to be implemented. Kim and Hogue (2012) developed the UCLA method, which used the soil wetness index (Jiang and Islam, 2003) derived from MODIS products as the downscaling factor to disaggregate the coarse resolution microwave observations of soil moisture. The above study showed that the UCLA method had similar performance with the Merlin method on spatially disaggregating the coarse spatial resolution land surface soil moisture in a semiarid region.

In this study, we developed a spatial downscaling approach namely the PKU method, which integrates the coarse spatial resolution soil moisture data and the temperature–vegetation–drought-index (TVDI) derived from MODIS LST and MODIS VI to spatially disaggregate the coarse spatial resolution soil moisture data. We also assessed the robustness of the PKU method by comparing its performance on spatial downscaling with the results of three published methods (i.e., the LST/VI triangle-based method, the Merlin method, and the UCLA method). The reminder of the paper is organized as following. In Section 2, we describe the biophysical characteristics of the study area, *in situ* soil moisture measurement networks, and the remotely sensed soil moisture data used in this study. Section 3 presents the methods for assessing the uncertainties of the remotely sensed soil moisture and the four methods for spatially disaggregating microwave observations of soil moisture. The modeling results are presented in Section 4. Finally, we summarize the findings of this work and discuss the limitations of the spatial downscaling method developed in this study.

2. Study area and data

In the study, we ran modeling experiments covering the Magqu soil moisture and soil temperature monitoring network, which locates in the northeastern part of the Tibetan Plateau (33°30′–34°15′N, 101°38′–102°45′E) (Fig. 1). This is one of the three *in situ* reference networks for monitoring soil moisture and soil temperature on the Tibetan Plateau (Su et al., 2011). The objective of building these field monitoring networks is to validate satellite-based soil moisture products and to obtain an improved understanding of various land surface processes in high elevation regions (Dente et al., 2012). In the study area, the elevations of the field monitoring sites range between 3430 m and 3750 m above seal level. Grassland is the dominant vegetation type, and climate there is wet and cold and with dry winters and rainy summers. The *in situ* soil moisture monitoring network in Magqu was installed in July 2008 by the Chinese Academy of Sciences (CAS), China.