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Inter-comparison of spatial upscaling methods for evaluation of satellite-based soil moisture

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S U M M A R Y

Soil moisture is a key factor in energy and water cycles. Many satellite missions have been planned and implemented for retrieving soil moisture globally. Because the spatial representativeness of a point-scale soil moisture station is rather limited, a station network needs setting up for scale-matching validation of satellite-based soil moisture products. Even so, an upscaling procedure is needed to upscale these station soil moisture values into area-wide one. However, such a procedure itself introduces uncertainties into the upscaled soil moisture. In this study, four upscaling methods (simple average, block kriging, model-based, and apparent-thermal-inertia-based) are inter-compared according to their performance stability for evaluation of soil moisture estimated by assimilating microwave signals into a land surface model. It is found that the performance of the model-based upscaling approach is the most unstable because model simulations are full of uncertainties for representing spatial variability of soil moisture. The block kriging upscaling method performs not worse than the simple averaging approach; the former may generate more representative soil moisture if the range of the soil moisture semivariogram used in the block kriging is comparable to the extent of a satellite footprint. The apparent-thermal-inertia-based upscaling is the most stable one, which has been developed with the aid of high-resolution satellite thermal data. All analyses indicate that choosing a suitable upscaling approach is important for the effective evaluation of satellite-based soil moisture. Otherwise, uncertainties hiding in the upscaling method will be incorrectly attributed to errors in satellite products, undermining our confidence in implementing them into practice.

1. Introduction

It is widely recognized that the acquisition of the spatiotemporal distribution of soil moisture at regional and global scales is of importance because it controls the exchanges of energy, water, and carbon between the land surface and the atmosphere. A deep understanding of these processes improves our skills in modeling climate and land hydrology (Hirabayashi et al., 2005; Koster et al., 2010; Seneviratne et al., 2010; Sheffield and Wood, 2007). Therefore, a number of microwave satellite missions have been initiated to map land surface moisture, such as the demised Advanced Microwave Scanning Radiometer for EOS (AMSR-E) (Njoku et al., 2003), the ongoing Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2010), and the upcoming Soil Moisture Active Passive (SMAP) mission (Entekhabi et al., 2010a). There are generally two methods to estimate soil moisture based on microwave signals. One is the inversion of a radiative transfer model based upon observed brightness temperatures with some ground ancillary information (Das et al., 2011; Jackson et al., 1999; Kerr et al., 2012). The other is the assimilation of brightness temperatures into a land surface model driven by atmospheric forcing (Crow and Wood, 2003; Lu et al., 2012; Montzka et al., 2011; Pan and Wood, 2006; Qin et al., 2009; Reichle et al., 2002; Yang et al., 2007). No matter which approach is used, soil moisture estimates from satellites have to be evaluated against in-situ measurements before applied in practice.

It is well known that in-situ soil moisture is merely representative over a small spatial scale (Bloschl and Grayson, 2001) because of its high spatial variability caused by spatial heterogeneity of soil, vegetation, topography, and precipitation. On the other hand, the spatial scale of satellite footprints is much larger than that of

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in-situ soil moisture measurements. This scale-mismatch has already been noticed in field calibration/validation campaigns for satellite soil moisture products (Al Bitar et al., 2012; Jackson et al., 2012, 2010; Sanchez et al., 2012). In order to eliminate such a mismatch, several spatial upscaling methods have been proposed to convert point-scale in-situ soil moisture to footprint-scale one.

There are generally four commonly used upscaling methods based on a station network (Crow et al., 2012; Qin et al., 2013). The first approach, which is the most often used, is the simple averaging of station data. The second approach is the block kriging, which utilizes the spatial correlation structure (semivariogram) of soil moisture measurements among stations to calculate area-wide soil moisture. The third approach is model-based, which uses the spatial pattern of soil moisture simulated by a land surface model to perform upscaling. The fourth approach is apparent-thermal-inertia-based, which merges in-situ data with soil moisture derived from fine-resolution satellite thermal signals.

As a matter of fact, it is very important to select a suitable upscaling approach to evaluating satellite-based soil moisture estimates. Otherwise, uncertainties intrinsic to the upscaling approach will be brought into the upscaled soil moisture, leading to biased evaluations. Therefore, the upscaling approaches themselves need to be carefully examined. In this study, we inter-compare the four upscaling methods by using their upscaled soil moisture to evaluate soil moisture estimated by microwave data assimilation on the Tibetan Plateau (TP) and the Mongolian Plateau (MP), and analyze the cause of different performances of the four upscaling methods.

2. Study area and data

Two soil moisture measuring networks deployed on the Tibetan Plateau and the Mongolian Plateau are used in this study. The Tibetan Plateau Soil Moisture/Temperature Monitoring Network (SMTMN) is located in the central TP and set up around the town of Naqu within an area of ~100 km × 100 km over 4500 m above sea level. The surface is relatively flat in most of this area although rugged in some places. The land cover is primarily alpine meadow with a few wetlands scattering. The SMTMN was initiated in 2010. Thirty-nine stations were first installed along four roads (white lines in Fig. 1a). In 2011, twenty more stations were installed. Some of them were used to replace the lost and damaged ones installed in 2010 and the others in conjunction with part of original stations form a medium network (green box in Fig. 1a) with a spatial size of 25 km × 25 km nested in the large one (red box in Fig. 1a). Five more stations were installed in a 5 km × 5 km area in 2012. These five new stations and nearby four stations compose a small network (blue box in Fig. 1a). At each station, both soil moisture and temperature are measured at depths of 0–5, 10, 20, and 40 cm, respectively, and the sampling interval is set to be 30 min. In this study, only surface soil moisture data that are measured at 28 stations in the large network (marked as red solid circles in Fig. 1a) from June 1 to September 30 2011 are used over the TP. The readers are referred to the article by Yang et al. (2013) for more information on this network.

The other network is located at Mandalgobi of Mongolia, which is a reference site of the Coordinated Enhanced Observing Period program (Kaihotsu et al., 2005). It covers a flat area of 120 km × 160 km with a mean elevation of 1380 m above sea level. The land cover type is primarily grassland. In this network, 12 Automatic Stations for Soil Hydrology (ASSH) and 6 Automatic Weather Stations (AWS) were deployed. Their geographic locations are shown in Fig. 1b. At ASSH, soil temperature and moisture are measured at depths of 3 and 10 cm and the sampling interval is 30 min. The AWS measure both meteorological data (wind, temperature, humidity, pressure, precipitation, and net radiation) and soil moisture/temperature profiles. Only surface soil moisture data from May 1 to September 23 2003 are used. Considering data continuity, we only use 14 stations marked as red solid circles in Fig. 1b.

3. Methodologies

In this study, the following way is taken to inter-compare and analyze these upscaling methods. First, an assimilation algorithm is applied to assimilate AMSR-E brightness temperatures or SMOS soil moisture products into a land surface model to obtain surface moisture estimates in the two networks. Second, the four upscaling approaches are implemented to upscale in-situ soil moisture to obtain area-wide values in the two network areas, respectively. Third, the upscaled soil moisture values are used to evaluate the assimilation results. Finally, the cause that leads to their different performances is investigated. In the following, the upscaling approaches and the assimilation system are briefly introduced.

3.1. Upscaling approaches

The aim of any upscaling method can be mathematically abstracted as:

$$\bar{\theta}_t^{\mathrm{ups}} = U(\boldsymbol{\theta}_t^{\mathrm{obs}}), \qquad (1)$$

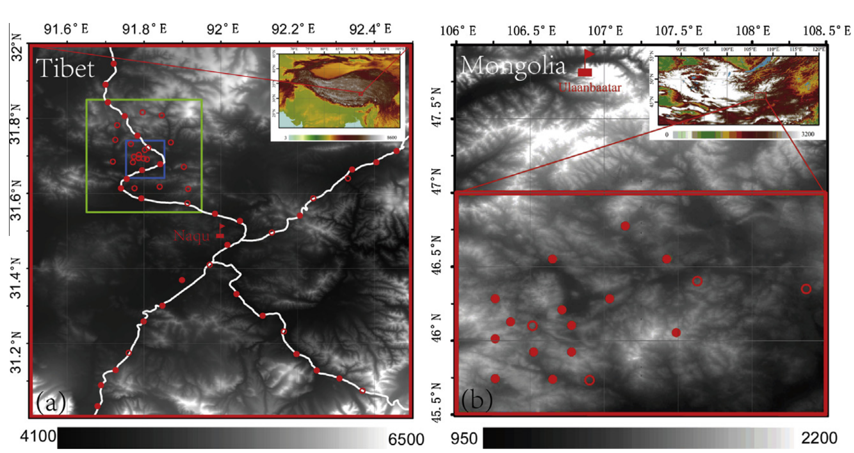

Fig. 1. Spatial distribution of soil moisture stations in two networks on (a) the Tibetan Plateau and (b) the Mongolian Plateau. The red circles illustrate the stations and the filled circles mark those used in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)