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Evaluation of Global soil moisture products over the Tibetan Plateau in Humid and Semiarid Climates

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Abstract: Accurate soil moisture data products are essential for implementing the food, energy, and water nexus approach. This study evaluates the accuracy of three globally available soil moisture data products, namely, (1) the satellite-based remote sensing product known as the Essential Climate Variable (ECV) which is a new product combining passive and active microwave measurements, (2) the global land surface simulation known as the

Global Land Data Assimilation System (GLDAS) driven by catchment model (referred to as "GLDAS1"), and (3) GLDAS driven by Noah model (referred to as "GLDAS2"). The study region is the Tibetan Plateau in China, characterized by high-elevation plateau and cold climate. The evaluation was made by comparison against a network of in-situ soil moisture measuring stations in two contrasting climates: the Maqu region (humid, elevation range 3430 – 3750 m.a.s.l), and the Naqu region (semiarid, elevation range 4100 – 6500 m.a.s.l). Results show that the observed soil moisture fields at both sites strong seasonal cycle. Both the ECV and GLDAS2 simulations capture well the temporal dynamics in observed soil moisture fields, at both sites. In terms of actual magnitudes, both ECV and GLDAS2 reproduced the average soil moisture at the Naqu site. However, they both underestimated the soil moisture at the Maqu site by 31% and 24%, at Naqu site by 20% and less than 5%. The GLDAS1 product, on the other hand, gives a constant value, and totally fails to capture the seasonal cycle at both sites. The performances of ECV and GLDAS2 is encouraging, however, the source of the bias at the humid site needs to be investigated further. The poor performance of GLDAS1 indicates that caution must be exercised in selecting appropriate land surface models.

Keywords: Soil moisture; ECV; GLDAS; Tibetan Plateau

1. Introduction

Soil moisture is a key variable in the Food-Energy-Water nexus approach. It determines irrigation water requirement as well as agricultural productivity. It controls the partitioning of available energy into sensible heat flux and latent heat flux, and the partitioning of rainfall into runoff and infiltration. Therefore, generating reliable and reasonable soil moisture data is an important step in the nexus approach. Traditionally, in-situ soil moisture sensors are deployed along with in-situ weather sensors to capitalize on existing measurement infrastructure. However, such "point" soil moisture measurements are inadequate to characterize soil moisture variability over a large domain due to the nature of inherent spatial variability in soil moisture (net effect of variability in precipitation and land surface characteristics), the sparse nature of in-situ stations, and the sub-optimal location of the sensors (suitable weather station locations do not often take into account differences in land surface characteristics). As a result, the spatial variability of soil moisture is often neglected in applications and research, limiting our ability to forecast weather [1, 2], to simulate hydrological processes [3-5], and to manage irrigation water among others [6].

Current technologies, particularly satellite remote sensing and land surface models, provide alternative information on spatial soil moisture variability. Although these technologies are advancing especially over the last few years with the launch of active microwave sensors and continental-scale land surface models, the resulting soil moisture fields are still subject to a variety of error sources. Quantifying the uncertainty in such soil moisture estimates is crucial to monitor and guide the improvement in estimation techniques as well as to utilize the data products properly taking into account the estimation uncertainties.

The objective of this study is to quantify the uncertainty in recent global soil moisture products, namely, (1) the satellite remote sensing-based product known as the Essential Climate Variable (ECV) developed by the European Space Agency, (2) the land surface simulation product from the Global Land Data Assimilation System (GLDAS) driven by catchment land surface model, and (3) the land surface simulation product from GLDAS driven by Noah land surface model. Our study region is the Qinghai-Tibetan Plateau (TP), a high-elevation region spanning both cold humid and cold semiarid climates. We use unique two experimental networks of in-situ soil moisture sensors, one in cold humid region and the other in cold semiarid region, as ground validation sites to evaluate the accuracy of the global soil moisture products at these two sites.

2. Data and Methods

2.1. Study Region and In-situ Soil Moisture Data

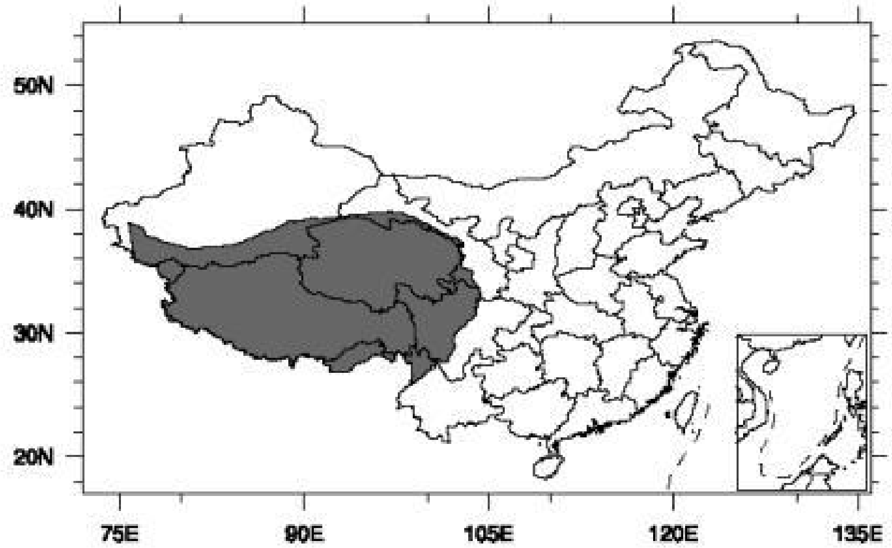
The Qinghai-Tibetan Plateau, also known as the Tibetan Plateau (TP), is a high-altitude plateau in a cold climate (mean-annual temperature below 0 ° C), and is located in Eastern China (see Fig. 1, upper panel). As shown in Fig. 1 (see middle and lower panels), the TP hosts two uniquely-dense experimental networks of soil moisture sensors[7], one located in the cold and humid region (i.e. the Maqu network) and the other located in a cold and semiarid region (i.e. the Naqu network). Site characteristics of the two networks are presented in Table 1[8].

Table 1. Characteristics of the Maqu and Naqu soil moisture measuring station networks in the Tibetan Plateau.

Site	Elevation (m)	Dominant Landcover	Climate	Precipitation (mm)	Soil Texture	Soil organic content
Maqu	3430~3750	Grassland	Cold humid	600	Silt loam	17.88%
Naqu	4100~6500	Alpine	Cold semiarid	400-500	Sand	9.18%

The Naqu network: Spreading over an area of 1° × 1° (i.e. N31°05′- N31°55′, E91°40′-E92°25′), this network is located in the central part of TP. The network consists of 56 instrumentation sites where soil moisture is measured at different depths at time intervals of 30 min. The sites have an average elevation ranging of 4500 m.a.s.l. The climate of the area is cold and semiarid with mean annual precipitation of 600 mm [9]. Further information on the network is given in [9, 10].

The Maqu network: Spreading over an area of 40 km × 80 km (i.e. (N33°35′- N34°05′, E101°45′-E102°45′), this network is located in the eastern part of TP. The network consists of 20 instrumentation sites where soil moisture is measured at different depths at time intervals of 15 min. The network, compared to the Naqu network, covers relatively lower altitudes with elevations ranging from 3430 m.a.s.l to 3750 m.a.s.l. The climate is cold and wet, with mean annual precipitation of 600 mm [9]. Further information on the network is given in [9-10].



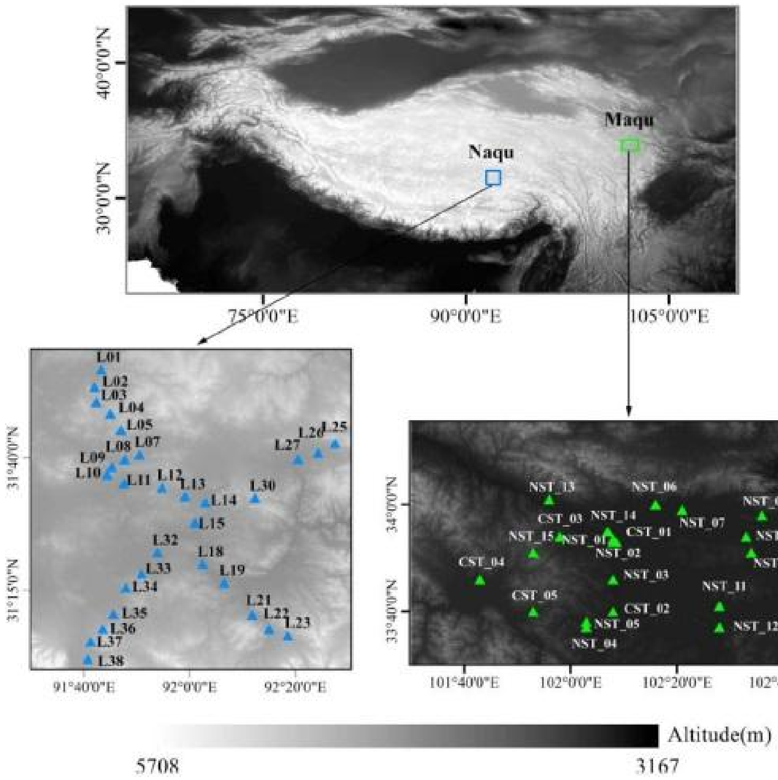


Figure 1. The study region, Tibetan Plateau, and its existing soil moisture measuring networks: (upper panel) the location of the plateau within china, (middle panel) the location of the two soil moisture measuring networks within the plateau, and (lower panel) the layout of the measuring stations within each networks, the Naqu network on the left, and the Maqu network on the right.

2.2. Global Soil Moisture Data Products to be Evaluated

We propose to evaluate two major global soil moisture products, namely, the ECV data product represensing satellite remote-sensing products, and the GLDAS data products representing global land surface models.

ECV Data Products: The Essential Climate Variable (ECV) soil moisture product, developed by ESA's Water Cycle Multi-mission Observation Strategy (WACMOS) and Soil Moisture Climate Change Initiative (CCI) projects, has three kinds of products depending on the satellite sensor used (active sensor only, passive sensor only, active-passive combined) [11-13]. In this study, we used the "combined product" that integrates both active and passive microwave measurements. This is a daily product with a spatial resolution of 0.25°. The dataset represents near-surface (~ 5 cm or so) soil moisture.

GLDAS Data Products: The Global Land Data Assimilation System (GLDAS) soil moisture simulation products are produced by the use of land surface models (LSMs) and data assimilation techniques. The input data used are multiple data sets serived from satelite products and atmospheric analyses. Different GLDAS soil moisture products exist depending on the LSM used. Moreover, there are two most used versions of GLDAS soil moisture products: GLDAS Catchment Land Surface Model (GLDAS1)and GLDAS Noah Land Surface Model(GLDAS2).Main difference between the two versions is that GLDAS2 climatologically more consistent than GLDAS1 as the data inputs in GLDAS1 were switched multiple times [7]. In this study, we considered the product of "catchment LSM" (hereafter referred to as "GLDAS1") and the product of "Noah-LSM: (hereafter referred to as "GLDAS2"). The GLDAS1 products are available at daily and 0.25° resolution, and span the time period 1948-2014, while the GLDAS2 products are available at 3-hourly and 0.25 ° resolution, and cover the period 2000-2019. Further information on these GLDAS products is available in Rodell et al[14].

2.3. Evaluation Methods

No single metric or statistic can capture all the attributes of environmental variables. Some are robust with respect to some attributes while insensitive to others [15]. The most commonly used two metrics to evaluate the accuracy of soil moisture retrievals are the correlation coefficient(R), and the root-mean-square error (RMSE). The respective formulas for the R and RMSE are:

$$R = \frac{\frac{1}{N}\sum_{i=1}^{N}(SM_i - \overline{SM})(insitu_i - \overline{insitu})}{\sigma_{SM}\sigma_{insitu}} \quad (1)$$

$$\text{and } RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(SM_i - institu_i)^2}, \quad (2)$$

where, N is the number of times, SM_i is soil moisture of ECV or each GLDAS products, $\overline{SM}$ is the average value of soil moisture observations from ECV or each GLDAS product, $institu_i$ is in situ soil moisture observations, and $\overline{insitu}$ is the average value of in situ soil moisture observation.

To represent the values for a large network, in situ soil moisture observations (0-5cm) averaged across all the sites is compared with the ECV, GLDAS1 and GLDAS2 data over the same rectangle area (see Figure 1). All the three soil moisture products are evaluated using the correlation coefficient (R), and the RMSE metrics. The units of soil moisture from GLDAS1 and GLDAS 2 are transformed into the same unit with the observed (Obv) (cm^3/cm^3) and ECV (cm^3/cm^3) using a simple formula.

$$\mathrm{SM}\ \left(\frac{\mathrm{cm}^3}{\mathrm{cm}^3}\right) = \mathrm{SM}(\mathrm{kg}\cdot\mathrm{m}^{-2}) \times \mathrm{d}/1.0 \times 10^{-3} \quad (3)$$

where, SM is different descriptions of soil moisture with different units, and d is the depth of soil moisture measurements.

Our evaluation method is primarily comparison of the satellite remote sensing based global soil moisture (i.e. ECV) and global land surface simulations (i.e. GLDAS1 and GLDAS2) against two networks of in-situ soil moisture measurements/observations (abbreviated as "Obv") at sites Naqu and Maqu. The comparison is done using time series plots, scatterplots, and summary statistics (primarily correlation coefficient and bias).

Although the global soil moisture products are available for a longer time scale, we limited this study to the period 01 January 2010 to 31 December 2014, due to availability window of the network in-situ measurements. The GLDAS datasets provide soil moisture values in units of [kg m^{-2}] over the entire thickness of the layer indicated, while the ECV and Obv provide data in volumetric soil moisture content. To make the units consistent, we divided the values [kg m^{-2}] by the depth (in mm) at which soil moisture measurement is taken.

Our spatial scale is the region represented by each soil moisture network (see Fig. 1, lower panels); i.e. Naqu network: N31°05′- N31°55′, E91°40′- E92°25′; Maqu network: N33°35′-N34°05′, E101°45′-E102°45′. Our "Obv" or reference soil moisture product for each region is obtained by averaging the in-situ soil moisture measurements in each region (i.e. 56 stations at Naqu, and 20 stations at Maqu). Similarly, for each global soil moisture product considered, we averaged the pixel-based data in each region. Our temporal scale of analysis is daily, and we have aggregated the sub-daily soil moisture products to daily.

3. Results

Figure 2 shows comparison of time series of daily soil moisture obtained from the remote sensing product (ECV) and the two GLDAS simulations (GLDAS1 and GLDAS2) against observed in-situ soil moisture measurements for the Maqu network region. Figure 3 displays the comparison in scatterplots. The observed soil moisture shows strong seasonal cycle, where volumetric soil moisture content varied from about 1% to 5%. The remote sensing product ECV captures the observed strong seasonal cycle with a correlation coefficient of 0.80, but with a large underestimation bias (31%). Similarly, the GLDAS2 (i.e. Noah LSM) captures the temporal variability of observed soil moisture with a correlation coefficient of 0.81, but with a large underestimation bias (24%). Both ECV and GLDAS2 products are strikingly similar to each other with a correlation coefficient of 0.71 and bias of 13% between each other. However, the GLDAS1 product (i.e. catchment-LSM) is almost a flat line (with a constant value of about 0.29) failing to capture the observed seasonal variability (correlation coefficient of 0.35 between GLDAS1 and observed soil moisture).

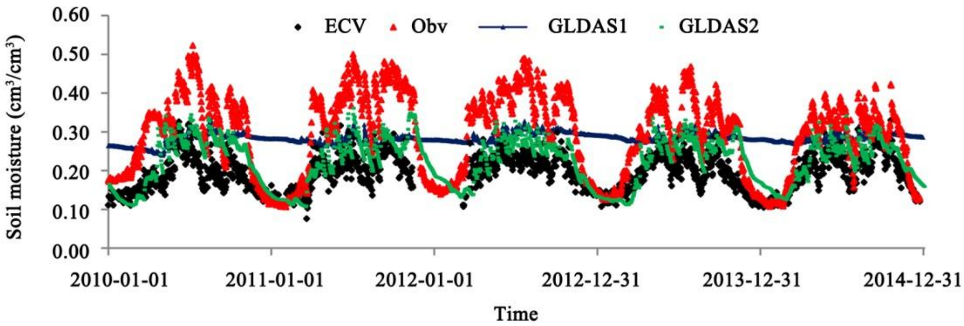


Figure 2. Comparison of soil moisture from ECV, GLDAS1 and GLDAS2 with in situ measurements from Maqu network region during period from 2010 to 2014.

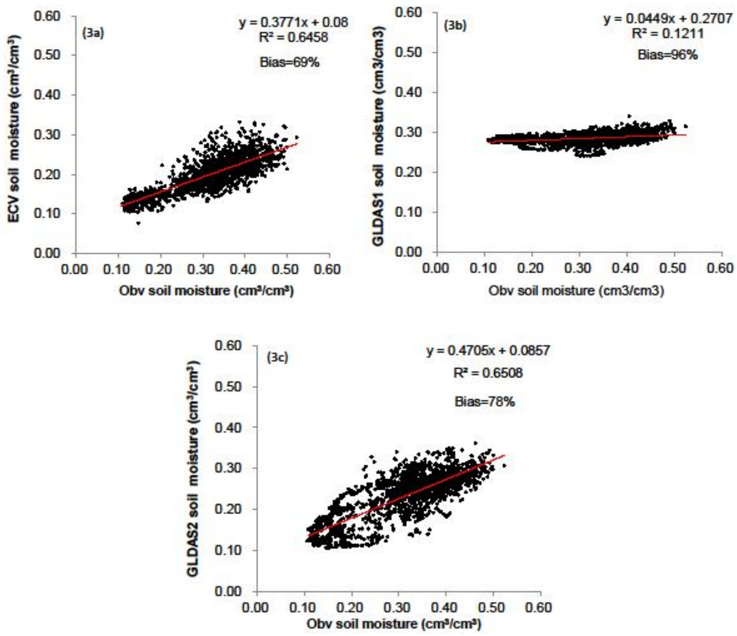


Figure 3. Soil moisture from ECV (3a), GLDAS1 (3b) and GLDAS2 (3c) versus in situ measurements in Maqu network region.

Figures 4 and 5 show the comparison of soil moisture products for the Naqu region. Both ECV and GLDAS2 products reproduce well the observed soil moisture in terms of the temporal dynamics of soil moisture (correlation coefficients of 0.88 and 0.83, respectively) and The ECV underestimated bias(20%), the GlDAS2 with a light actual magnitudes (bias less than 5%). Compared between the two products, GLDAS2 outperforms ECV. However, the GLDAS1 products give a constant value around 0.27, and fail totally to capture the temporal dynamics in observed soil moisture.

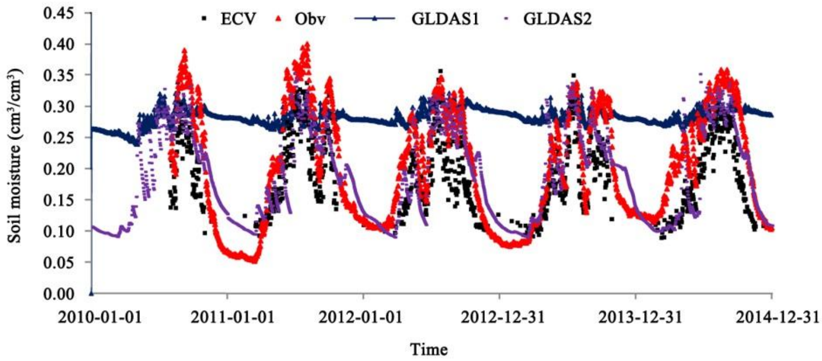


Figure 4. Comparison of soil moisture in ECV, GLDAS1 and GLDAS2 with in situ soil moisture measurements from Naqu network region during the period from 2010 to 2014.

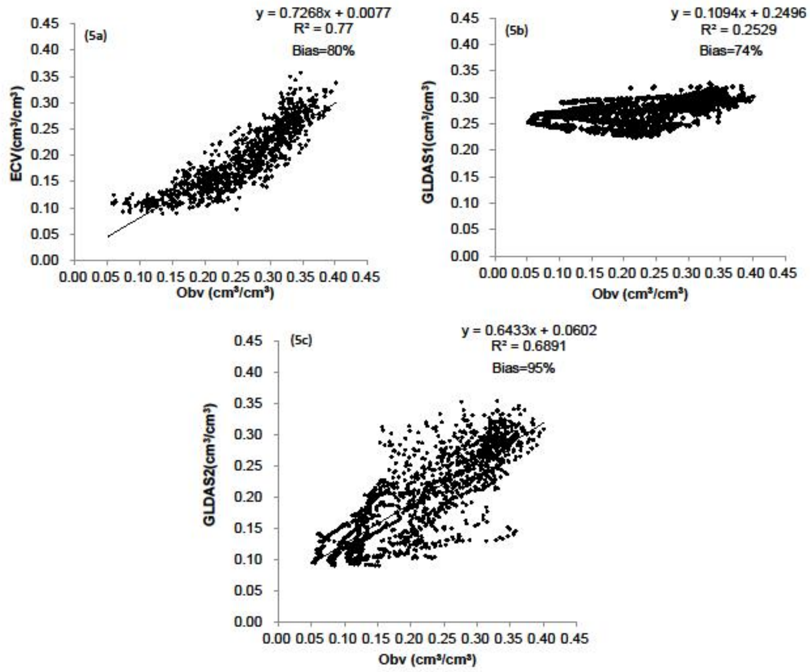


Figure 5. Soil moisture data from ECV (5a), GLDAS1 (5b) and GLDAS2 (5c) versus in situ measurements in Naqu network region during the period from 2010 to 2014.

4. Discussion and Conclusions

Food-energy-water nexus studies are hindered by the lack of spatially and temporally distributed soil moisture estimates. Emerging satellite-based remote sensing technologies and global land surface simulations are currently providing global soil moisture products, however, comprehensive evaluation of such products is essential before any usage. In this study, we assessed the accuracy of global soil moisture products obtained from satellite-based remote sensing and Global Land Data Assimilation System (GLDAS) land surface model (LSM) simulations. Specifically, we considered three soil moisture data products: (1) the ECV product that is derived by blending active and passive microwave remote sensing, (2) the catchment-LSM GLDAS (GLDAS1), and (3) the Noah-LSM GLDAS (GLDAS2).

The assessment was performed in the Tibetan Plateau (TP) at two sites that represent contrasting climates: (1) the Naqu site with a cold and semiarid with mean annual precipitation of 600 mm, and (2) the Maqu site with a cold and humid with mean annual precipitation of 4500 mm. Both sites are equipped with a network of in-situ soil moisture measuring stations. The site-averaged in-situ station measurements were used as a reference to compare the global soil moisture products. The study period covers five years, from 2010 to 2014. The observed soil moisture at both sites show strong seasonal cycles. Our evaluation results reveal the following:

1) The satellite-based soil moisture product ESA CCI captures well the temporal dynamics in observed soil moisture fields at both sites, with a correlation coefficient of 0.80 and 0.88, for the Maqu and Naqu sites, respectively. However, the ESA CCI product exhibits different bias characteristics at both sites: it has large underestimation bias (31%) and (24%) for the Maqu site and Naqu site respectively.

2) The performance of the GLDAS simulations depends on the land surface model used. The Noah-LSM simulations capture well the temporal dynamics in observed soil moisture fields at both sites, with a correlation coefficient of 0.81 and 0.83, for the Maqu and Naqu sites, respectively. However, the Noah-LSM simulations underestimate the average soil moisture by 20% for the Maqu site, while they are relatively unbiased for the Naqu site (bias less than 5%). On the other hand, the catchment-LSM simulations give a nearly constant value over the five-year period, and fail to capture the temporal dynamics in soil moisture fields, at both sites.

Finally, we conclude that the satellite-based ESA CCI and the Noah-LSM GLDAS simulation can reasonably capture the temporal dynamics in observed soil moisture fields at both sites, albeit with strong underestimation bias in the Maqu site. However, the Catchment-LSM GLDAS simulation fails to capture the temporal dynamics in observed soil moisture fields. Based on this work, we recommend further work in the following areas in different regions of the world: (1) understand and examine the impacts of different land surface models and their parameterizations, and (2) quantifying the source of bias in the cold and semiarid region.

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