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First evaluation of SMOS L2 soil moisture products using in situ observation data of MAVEX on the Mongolian Plateau in 2010 and 2011

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Abstract:

This study tried to make a first evaluation of SMOS L2 soil moisture data (ver. 4.00) obtained during ascending orbits using in situ hydrological observation data of a 120 km by 120 km study area on the Mongolian Plateau from April to August in 2010 and from May to September in 2011. Unfortunately, as we could hardly obtain any available data of SMOS L2 soil moisture from descending orbits for evaluation because of Radio Frequency Interferences (RFI), the evaluation results of SMOS L2 soil moisture products only from ascending orbits (5:30–7:00 in local time) were actually analyzed. Although SMOS slightly underestimated the soil moisture contents at a depth of 3 cm, good matching was observed in the response patterns of SMOS and in situ soil moisture data and the differences between these factors were not large. Accordingly, small values of RMSE and bias were obtained between SMOS soil moisture and in situ measured soil moisture at a depth of 3 cm. SMOS was able to estimate surface soil moisture contents with an accuracy of about 0.045 ($m^3\ m^{-3}$) in steppe areas of the Mongolian Plateau.

KEYWORDS soil moisture; evaluation; water cycle; Mongolia; SMOS

INTRODUCTION

As discussed in many previous studies (*e.g.* Beljaars *et al.*, 1996), it is very important to study soil moisture behavior in the water cycle and with respect to climate change. Such behavior influences plant growth and small animal life, especially in semi-arid and arid areas, where precipitation is highly variable in both space and time. However, it is difficult to acquire sufficient information regarding the behavior of soil moisture in such areas at a large scale using traditional in situ observation methods. Accordingly, satellite observations of soil moisture are potentially an effective alternative.

The Soil Moisture and Ocean Salinity (SMOS) mission of the European Space Agency (ESA) was successfully launched on 2 November 2009 to provide global surface soil moisture and sea surface salinity data. SMOS is equipped with the Microwave Imaging Radiometer by Aperture Synthesis (MIRAS), which is an L-band two dimensional aperture synthesis interferometric radiometer with multi-angle and polarimetric imaging capabilities. Since its launch, the SMOS mission has been measurement of the global soil moisture on the surface of the Earth with a target accuracy of 0.04 ($m^3\ m^{-3}$), a spatial resolution better than 50 km and a temporal resolution of 3 days (Kerr *et al.*, 2001).

The 2010 SMOS L1 data set has been processed by the ESA and the European Space Astronomy Center. The processing from the SMOS brightness temperatures to the SMOS L2 soil moisture products is shown in Array Systems Computing Inc. (2011). However, the Center d'Ètudes Spatiales de la BIO sphère and the Centre National d'Ètudes Spatiales have reprocessed the L2 soil moisture (ver. 4.00 of the L2 algorithms). The brightness temperature of the SMOS soil moisture data is computed using an L-MEB (L-band microwave emission of the biosphere: Wigneron *et al.*, 2007). According to Wigneron *et al.* (2001), the soil effective temperature of the brightness temperature of the INRA (Institut National de le Rocherche Agronomique) Avignon soil type was found to be very close (within ±0.5 K) to the soil temperature measured at a 5 cm depth below the surface.

Kerr *et al.* (2012) gives a good overview of the algorithm of the soil moisture retrieval algorithm and discusses the soil moisture retrieval approach, the general radiative transfer equation, and the effectiveness of the algorithm using the latest validation results.

It is necessary to check the reliability and accuracy of soil moisture data from MIRAS to enable precise validation and/or evaluation in as many and various areas as possible. Sanchez *et al.* (2012) evaluated the SMOS L2 soil moisture products (ver. 4.00) in the 35 km × 35 km site of agricultural surface conditions in Spain and Jackson *et al.* (2012) performed an evaluation for four experimental watersheds in North America with different surface conditions and individual pixel sizes of less than 610 km^2. These studies showed that SMOS estimated soil moisture with a root mean square deviation (RSMD) of 0.044 $m^3\ m^{-3}$ and a root mean

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square error (RMSE) of 0.043 $m^3\ m^{-3}$. In order to know precisely the measurement accuracy of SMOS soil moisture, more evaluation should be made in various sites with different surface conditions and a reasonable size using the same data from version 4.00. Fortunately, we have been operating a 120 km × 120 km validation site on the Mongolian Plateau (Kaihotsu *et al.*, 2009). This study area has been used for the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) and the AMSR2 soil moisture measurement algorithm of the Mongol AMSR-E/AMSR2 Validation Experiment (MAVEX) of the joint cooperation study between Hiroshima University and the Japan Aerospace Exploration Agency (JAXA). An evaluation of the SMOS L2 soil moisture products was also made there as a representative pastoral area in central Asia.

The purpose of the present study was to undertake a first evaluation of the SMOS L2 soil moisture product data obtained from ascending orbits using soil moisture and meteorology data collected in situ within our study area on the Mongolian Plateau.

METHODS

Study area

The area used for evaluation of the SMOS L2 soil moisture data is located in the Mongolian Plateau. The water cycle stations used for the evaluation are shown in Table I, and the distribution of these stations with respect to three target areas used for the evaluation is shown in Figure 1. The study area (SA) primarily consists of flat terrain covered with pasture grass and sparse shrubs with an altitude between 1,300 m and 1,600 m above sea level. There are also several small mountains wit a height of about 1,600 m above sea level in the southeast portion of the study area. Three target areas (M1, M2 and M3) each of single pixel size were used for the evaluation. M1 and M2 had seven stations each, while there were five stations in M3 (Figure 1). The sampling points of SMOS are also shown in this figure.

In early summer, bare surface conditions are present in some areas. In addition, frozen soils occur from late October to mid-April. Soil hydraulic properties in the study area were investigated by Yamanaka *et al.* (2007) and were found to play a significant role in regulation of the surface soil moisture pattern.

In situ water cycle observation stations

As shown in Figure 1 and Table I, three automatic weather stations (AWSs) and 10 automatic stations for soil hydrology (ASSHs) were used to measure the in situ soil moisture in the study area. Fundamental elements of meteorology and soil moisture were precisely monitored by AWSs with a time interval of 30 minutes. ASSHs monitor soil moisture and soil temperatures bi-hourly at depths of 3 and 10 cm. All of the water cycle station sensors were calibrated and checked relative to a base marker and/or the Japanese Meteorological Agency standard in the laboratory prior to installation (Kaihotsu *et al.*, 2009).

The AWS and ASSH monitoring data were successfully and continuously obtained from April 2010 to September 2011 for evaluation of soil moisture data obtained by SMOS L2 in the ascending orbit. According to the AWS observation data, the daily mean air temperatures at the MGS station during the observation periods from April to August in 2010 and from May to September in 2011 were 14.4°C and 17.2°C, respectively. In addition, there were frequent rainfall events during these periods totaling 90 mm and 88.6 mm, respectively. Similar results were obtained from the other two AWSs.

In situ soil moisture measurements

The TDR (time domain reflectometry) soil moisture probes were also tested for probe error in the laboratory before installation using a polyvinyl chloride column and Toyoura standard sand of 0.1 mm in diameter. As shown in Kaihotsu *et al.* (2009), the relative accuracy of the TDR probes ranged from ±0.005 ($m^3\ m^{-3}$) (at a soil water content of 0.05 $m^3\ m^{-3}$) to ±0.018 ($m^3\ m^{-3}$) (at a soil water content of 0.38 $m^3\ m^{-3}$).

TDR was used to measure the in situ volumetric soil moisture contents. Two TDR soil moisture probes (TRIME IT, IMKO) with two stainless-steel rods 11 cm long, 3.5 mm in diameter, and 2 cm in spacing were installed horizontally at 3 and 10 cm depths at each AWS and ASSH. The effective measurement area of each probe was an ellipse of about 7.5 cm around the major axis and about 3 cm along the minor axis of the cross section with a length of 11 cm. As

Table I. In situ water cycle stations (No data at 3 cm depth because of broken TDR probe of ASSH820)

Name	Lat. (N)	Lon. (E)	Alt. (m)
MGS AWS	45°44'34.9"	106°15'52.2"	1393
DRS AWS	46°12'31.2"	106°42'53.0"	1297
BTS AWS	46°46'35.4"	107°08'32.2"	1371
ASSH811	45°55'22.5"	106°54'30.2"	1450
ASSH813	46°06'10.0"	106°46'47.2"	1318
ASSH814	46°16'57.6"	107°02'13.1"	1350
ASSH815	46°06'10.0"	106°31'21.2"	1383
ASSH816	46°24'06.1"	106°27'01.5"	1344
ASSH817	45°44'23.4"	106°39'05.5"	1342
ASSH818	46°49'20.2"	106°39'04.2"	1372
ASSH819	46°16'57.6"	106°15'52.1"	1407
ASSH820	45°55'22.5"	106°31'21.2"	1422
ASSH5N	46°33'08.9"	107°25'22.0"	1383

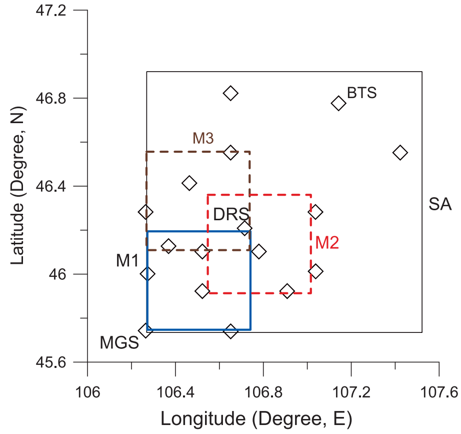

Figure 1. Target areas and in situ stations (◇)

a result, the TDR probe at a depth of 3 cm measures the volumetric water content in the soil vertically from about 1.5 to 4.5 cm in depth. The SMOS measures soil moisture in a thin surface soil layer; therefore, the TDR probes used in this study were adequate for the in situ soil moisture measurement phase of the evaluation.

In situ soil moisture data for evaluation

We obtained the in situ hourly area-averaged soil moisture contents and soil temperatures at depths of 3 cm and 10 cm, as well as the rainfall recorded at all AWSs in the study area during the 2010 and 2011 SMOS evaluation periods. Because the soil moisture contents of the ASSHs were monitored bi-hourly, we calculated the in situ hourly soil moisture contents and soil temperatures using linear interpolation. The in situ area-averaged soil moisture contents and soil temperatures referred to the arithmetic mean of the hourly soil moisture contents and soil temperatures from all of the stations. We also calculated the in situ hourly area-averaged soil moisture contents in the study area using the isohyetal method in the case of the lowest and highest soil moisture contents, but the maximum difference was only about 0.019 (m^3 m^{-3}). Therefore, the in situ hourly area-averaged soil moisture contents calculated by the arithmetic mean method were used to evaluate the SMOS L2 soil moisture data and were used for the subsequent analyses conducted in this study.

Some water cycle stations in the study area recorded several unexpected spikes in soil moisture contents, which was likely a result of local rainfall events. The difference between the highest and lowest in situ soil moisture contents at a depth of 3 cm among stations was about 0.35 (m^3 m^{-3}) when soils thawed in early April of 2010. The mean difference of the soil moisture contents at a depth of 3 cm for all stations was about 0.07 (m^3 m^{-3}) in June and about 0.08 (m^3 m^{-3}) in August of 2010 and 2011. However, with the exception of the aforementioned periods, most differences in soil moisture at a depth of 3 cm among stations were less than 0.05 (m^3 m^{-3}). The difference in soil moisture at a depth of 10 cm among all stations was generally smaller than that at a depth of 3 cm.

The in situ area averaged soil moisture contents at 3 cm varied widely and frequently and responded significantly to rainfall events. Specifically, values ranged from 0.04 (m^3 m^{-3}) to about 0.18 (m^3 m^{-3}) in 2010 and from 0.05 (m^3 m^{-3}) to about 0.21 (m^3 m^{-3}) in 2011. Conversely, the in situ area-averaged soil moisture contents at 10 cm did not change greatly when compared to those observed at 3 cm. The soil moisture contents at 3 cm were generally slightly lower than those at 10 cm, except in the case of strong rainfall events. With drainage following rainfall, the in situ soil moisture contents at 3 cm decreased more than those at 10 cm. The in situ soil temperature at MGS also changed widely and frequently, ranging from 0.02°C to 36°C and 11.5°C to 36.7°C from mid-April to August in 2010 and from mid-May to mid-September in 2011, respectively. Soil temperatures less than zero were observed from mid October to mid-April.

Taken together, the results observed in the present study suggest that the in situ surface soil moisture contents behave dynamically.

SMOS L2 soil moisture products data for evaluation

The small amount of SMOS L2 data pertaining to soil moisture products for evaluation was primarily due to the RFI pollution. Therefore, we attempted to analyze all the "N_RFI_X" and N_RFI_Y" data in the dataset to investigate the conditions of sampling points contaminated by the RFI. These two parameters are suspected of being contaminated by the RFI (Indra Espacio S. A., 2011). Specifically, the number of retrieved sampling points and sampling points contaminated by the RFI were analyzed (Figures 2 and 3).

There were originally 71 SMOS sampling points for our study area. Unfortunately, because we did not know the intensity of the RFI, we occasionally retrieved sampling points pertaining to areas that had been contaminated by RFI. Comparison of results obtained during descending orbits with those obtained during ascending orbits resulted in there being few data pertaining to descending orbits available for evaluation, considering that the existence rate was more than 50% in each target area. Additionally, as shown in Figure 2b, no sampling points were retrieved from areas contaminated by the RFI on many SMOS observation dates. Overall, these findings imply that RFI had a strong impact on sampling points, especially descending orbits. As a result, the data available for evaluation consisted of 20 soil moisture products collected in ascending orbits in 2010 and 33 collected in 2011. Conversely, there was only one product collected in the descending orbit in 2010 and four collected in descending orbits in 2011. Because this obviously did not provide sufficient data for analysis, SMOS L2 soil moisture products obtained from descending orbits were not evaluated in this study.

We arithmetically averaged all of the values from the

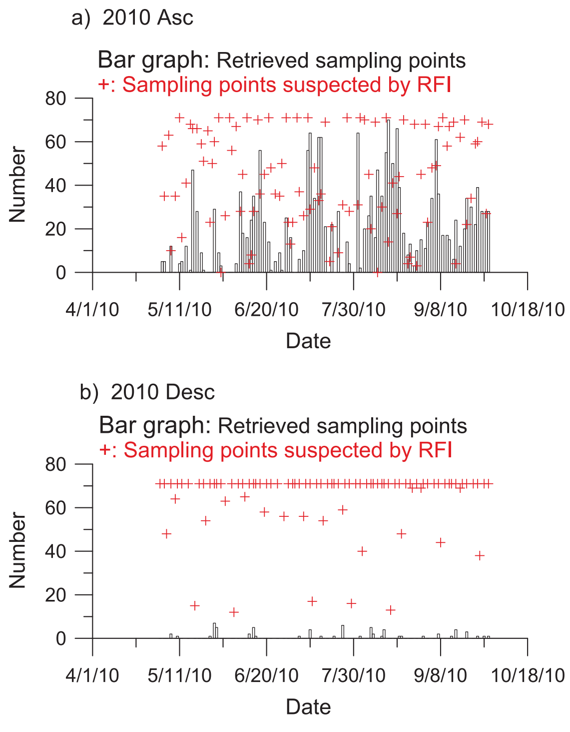

Figure 2. Change of number of retrieved samples and sampling points suspected by the RFI for each observation date in the SMOS L2 soil moisture products dataset in 2010

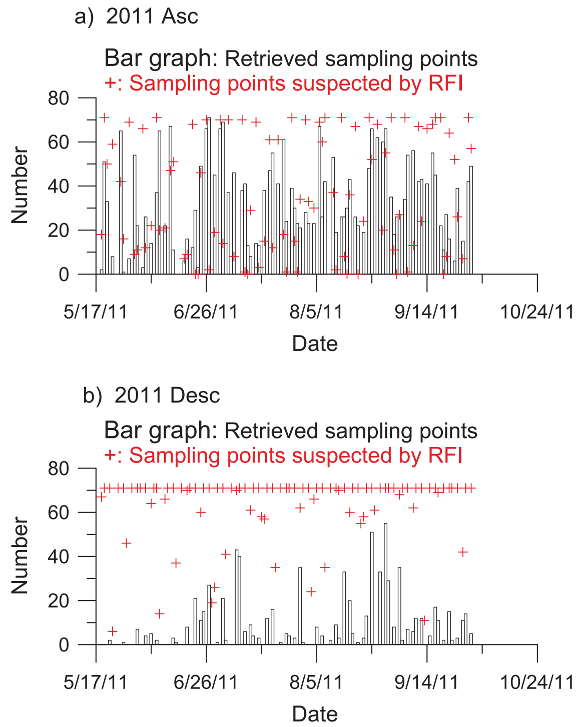

Figure 3. Change of number of retrieved samples and sampling points suspected by the RFI for each observation date in the SMOS L2 soil moisture products dataset in 2011

available sampling points in each target area and used actual data from SMOS L2 soil moisture products for evaluation.

RESULTS AND DISCUSSION

The results of evaluation of the SMOS L2 soil moisture data obtained from ascending orbits and pertaining to target area M1 are shown in Figure 4.

The SMOS in the ascending orbit measured soil moisture between 5:30 a.m. and 7:00 a.m. (local Mongolia time).

The area soil moisture contents were calculated from the SMOS L2 soil moisture data by arithmetically averaging the data collected from 12 (2010) and 13 (2011) sampling points in the target areas of M1. Since each sampling point covers about 50 km by 50 km (one pixel size of SMOS), the evaluation area covered by the SMOS data can be considered to be slightly larger than each target area in this calculation.

As shown in Figure 4, good matching was observed in the response pattern, even though there were limited SMOS soil moisture data available, and the difference between SMOS soil moisture data and the in situ soil moisture contents at 3 cm was not particularly large. However, the soil moisture measured by SMOS after the peak was lower than the moisture contents measured in situ.

In the low range of in situ soil moisture of less than 0.1 (m^3 m^{-3}), the measurement depth of the L band is more than 20 cm (Engman and Gurney, 1991). Therefore, we also evaluated the SMOS soil moisture data using the soil moisture contents determined in situ at 10 cm (Figure 4). However, as with the 3 cm data, it was very difficult to

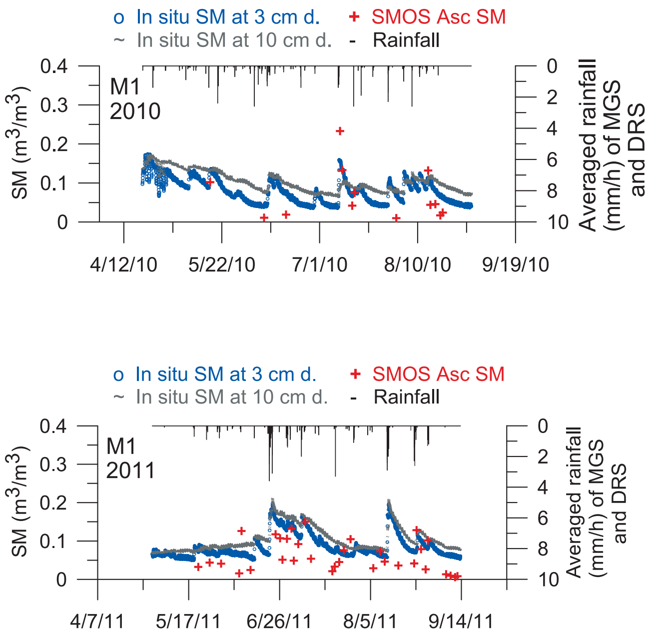

Figure 4. Comparison of SMOS soil moisture of L2 soil moisture products in ascending orbits with in situ area averaged soil moistures at 3 cm and 10 cm depths in M1 in 2010 and 2011 (SM is soil moisture)

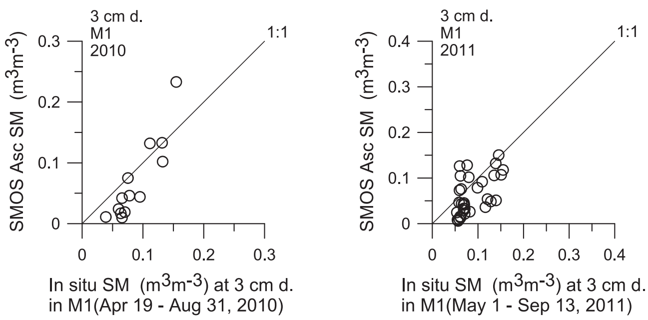

Figure 5. Relationship between in situ 3 cm depth and SMOS soil moistures in M1 in 2010 and 2011 (SM is soil moisture)

identify a good response pattern using the 2010 data. Overall, differences were apparent between the SMOS soil moisture and in situ soil moisture at 10 cm.

We also compared SMOS L2 soil moisture data from ascending orbits with in situ soil moisture contents in the M2 and M3 target areas using the same procedure. As with the M1 case, a good response pattern and little difference between SMOS soil moisture data and in situ soil moisture contents were apparent for all results obtained at a depth of 3 cm in M2 and M3. The change patterns were nearly the same as the M1 ones.

Figure 5 shows the relationships between SMOS soil moisture and in situ soil moisture at depths of 3 cm and 10 cm for the M1 target area from April 19 to August 30 in 2010 and from May 1 to September 13 in 2011, respectively. During both periods, the soils were completely unfrozen. Plots were mostly scattered around the 1 : 1 line and the SMOS soil moisture data varied with the in situ soil

Table II. Evaluation of soil moisture products/estimations in 2010 and 2011 (RMSE and Bias are in $m^3\ m^{-3}$. R is the correlation coefficient. N is the number of data)

Products	Target area	Year	In situ soil moisture measurement depth	RMSE	Bias	R	N
SMOS (Ascending)	M1	2010	3 cm	0.041	−0.020	0.910	13
			10 cm	0.067	−0.028	0.234	
		2011	3 cm	0.044	−0.026	0.550	33
			10 cm	0.061	−0.047	0.507	
SMOS (Ascending)	M2	2010	3 cm	0.045	0.001	0.890	13
			10 cm	0.058	−0.009	0.582	
		2011	3 cm	0.041	−0.008	0.501	33
			10 cm	0.053	−0.031	0.532	
SMOS (Ascending)	M3	2010	3 cm	0.044	−0.018	0.863	13
			10 cm	0.044	−0.024	0.875	
		2011	3 cm	0.054	−0.022	0.444	33
			10 cm	0.064	−0.041	0.376	

moisture contents. The results of statistical analysis of data from all target areas are shown in Table II.

According to the bias values (Table II), the soil moisture contents from the SMOS were slightly underestimated. However, these values were better than the bias values obtained by Sanchez *et al.* (2012) and Wigneron *et al.* (2012) and mostly equal to those of Jackson *et al.* (2012). At a depth of 3 cm, the RMSE values ranged from 0.041 ($m^3\ m^{-3}$) to 0.054 ($m^3\ m^{-3}$) and significant R (correlation coefficient) values were observed, suggesting that the data were well correlated (Table II). The averaged value (0.045 $m^3\ m^{-3}$) of RMSE at a 3 cm depth calculated from Table II was slightly different from that of Jackson *et al.* (2012) and was nearly equal to the target value (0.04 $m^3\ m^{-3}$) of the measurement accuracy of SMOS. As there was not enough data to make an evaluation in this study, the small difference may be due to the insufficient analysis.

Regarding 10 cm depth, all values obtained in Table II at 10 cm varied widely and more so than those obtained at 3 cm.

These results imply that there is relatively good agreement between the in situ soil moisture contents at a depth of 3 cm and the SMOS soil moisture data measured during ascending orbits. Accordingly, it is likely that SMOS soil moisture measurements of the steppe areas of the Mongolian Plateau are highly accurate.

CONCLUSIONS

The results of this study are summarized as follows:
1) There was insufficient data for SMOS L2 soil moisture products due to RFI pollution. Especially, the SMOS L2 soil moisture products in descending orbits were unavailable.
2) Successful evaluation of the SMOS L2 soil moisture data measured during ascending orbits was achieved for the first time in a study area on the Mongolian Plateau. The SMOS L2 soil moisture data gave a reasonable match between changes and the distribution of soil moisture in the study area.
3) The SMOS soil moisture data only slightly underestimated the in situ soil moisture contents at 3 cm, but was considerably less effective at matching the in situ soil moisture contents at 10 cm. Moreover, small RMSE and bias values (0.045 $m^3\ m^{-3}$ and −0.016 $m^3\ m^{-3}$, respectively) were observed between the SMOS L2 soil moisture data and in situ soil moisture at 3 cm. SMOS may be able to estimate surface soil moisture contents with high accuracy corresponding to the target value (0.04 $m^3\ m^{-3}$).

Overall, the quality of the SMOS L2 soil moisture data was high for large scale surface soil moisture monitoring.

We did not obtain sufficient SMOS L2 soil moisture data to enable detailed analysis of the evaluation data. It is also important to evaluate differences in SMOS soil moisture estimated during ascending and descending orbits. Therefore, further evaluations are required using fuller datasets to enable a more precise discussion.

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