Validation of Soil Moisture Estimation by AMSR-E in the Mongolian Plateau

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Abstract

During the summer of 2000, the monitoring of the water cycle using ground-based long-term monitoring data began to be used as ground truth for ADEOS-II (Advanced Earth Observing Satellite-II) /AQUA validation in the study area (160 km by 120 km) of the Mongolian Plateau. Since 2002, the AMSR-E (Advanced Microwave Scanning Radiometer for EOS) has successfully monitored the surface soil moisture on a global scale. In this study, we have attempted to validate the AMSR-E standard algorithm of JAXA using the JAXA standard product data (Ver. 5.0) of the AMSR-E soil moisture estimation and ground-based long-term monitoring data in the study area from 2002 to 2007. Although the standard product slightly overestimated the soil moisture, a good correlation was found between the AMSR-E soil moisture product and the ground-based soil moisture in Mongolia, and a reasonable matching of the change and distribution of soil moisture between them was found. The results suggest that the quality of the standard product of AMSR-E is good and basically useful for surface soil moisture monitoring over large areas of the steppe.

Keywords: soil moisture, AMSR-E, validation, water cycle, Mongolian Plateau

1. Introduction

Soil moisture plays an important role in the water cycle. Many studies have discussed the importance of soil moisture behaviors in the water cycle and in climate change. Soil moisture behaviors also influence plant growth and the lives of small animals, especially those living in semi-arid and arid areas where precipitation is highly variable, both in space and in time. However, it is not easy to acquire sufficient information on the behavior of soil moisture in such lands over a large scale using the traditional ground-based observation method. As is well known, satellite observations of soil moisture could be an effective alternative for determining soil moisture behaviors over large areas.

The Earth observation satellite AQUA equipped with the AMSR-E (Advanced Microwave Scanning Radiometer for EOS) that was launched in 2002 was equipped to be used for the regional and global observation of soil moisture. The AMSR-E uses a frequency range of 6.9 to 89.0 GHz, giving a spatial resolution that varies from 70 km to 6 km. In order to estimate soil moisture by AMSR-E, it is indispensable that an algorithm be established for soil moisture observation. There have been some attempts to develop algorithms for soil moisture estimation using a passive microwave remote sensor. However, reliable algorithms in terms of adequate measurement accuracy have yet to be developed. A few types of observations of ground-based soil moisture intended for AMSR validation have been tried in the Southern Great Plains. However, these measurements do not satisfy the conditions in terms of time interval, continuity or measurement area scale (10^3 – 10^4 km^2) in the ground truth soil moisture data. These validation conditions need to be made in order to be able to develop a high quality algorithm.

JAXA EORC has become the standard product for soil moisture data for the AMSR-E since 2003 (http://www.sharaku.eorc.jaxa.jp). Hydrologists and meteorologists have used the data in many studies, including those related to the water cycle. The quality of the soil moisture product is a significant limitation of the standard algorithm.

The purpose of this study is to validate the standard soil moisture algorithm both precisely and substantially, using the...
soil moisture product and monitoring ground-based soil moisture data within the study area of the Mongolian Plateau over a long period of time.

2. Methods

2.1 Validation study area

The study area used for the validation of the AMSR/AMSR-E observations in 2000 is shown in Fig. 1. The area is set in the Mongolian Plateau between the Mandalgobi site (MGS: 45° 46.175′N, 106° 16.539′E) and Choyr (CRS: 46° 21.133′N, 108° 22.509′E), and is studded with villages of various sizes. The study area was 160 km by 120 km in size and consisted of terrain that was mostly flat and covered with pasture grass and sparse shrubs with an altitude mostly between about 1300 m to 1600 m above sea level. The physical parameters of the study soils at the monitoring points are shown by Yamanaka et al. They highlight the fact that soil-hydraulic properties are significant in the regulation of the moisture pattern of surface soil moisture in the study area.

2.2 Ground-based water cycle monitoring stations

Ground-based water cycle stations have been successfully monitoring some of the fundamental elements of meteorology and soil moisture since 2000 and 2001, and several complementary intensive field observations during the summer had been carried out by 2007 for the AMPEX (ADEOS-II Mongol Plateau Experiment for ground truth)/MAVEX (Mongol AMSR/AMSR-E/ALOS Validation Experiment) projects and CEOP (Coordinated Enhanced Observing Period).

Hourly ground-based monitoring was planned for the acquisition of routine data from the networks of AWS (Automatic Weather Station) and ASSH (Automatic Station for Soil Hydrology). Four AWS and twelve ASSHs (Fig. 1, Table 1) were installed in the study area in 2000 and 2001, respectively. The measurement elements of the AWS were air temperature, humidity, air pressure, net radiation, soil surface temperature, soil temperature, soil heat flux, soil moisture and wind speed/direction. The depths of the soil moisture monitoring were 3 cm, 10 cm, 40 cm and 1 m for the MGS, DRS and DGS and 3 cm, 10 cm, 20 cm and 40 cm for the BTS. ASSHs have been monitoring soil moisture and soil temperatures at depths of 3 and 10 cm, respectively. All of the meteorological sensors employed were calibrated and checked relative to a base marker and/or the Japanese Meteorological Agency standard in the laboratory before installation.

The AWS monitoring data were successfully obtained from September 2000 to August 2007 at three AWS (MGS, DRS and BTS), and from September 2000 to June 2006 at DGS. Unfortunately, data from the AWS at DGS terminated during the summer of 2006 because the electric power system and some of the sensors failed. Figure 2 shows a sample of the AWS monitoring results at MGS for the period 2001 to 2007.

The air temperature showed a sinusoidal pattern varying from 38.4°C (2007) to -34.7°C (2001). The mean annual air temperature at MGS in 2007 was the highest in the last seven years (Fig. 2). The maximum value of the annual precipitation was 156 mm in 2003 and the minimum was 76 mm in 2007. Statistical analysis showed a slight decline the annual precipitation over the last six years (2002 to 2007). However,
the air temperature has been increasing slightly since 2000. Similar phenomena were observed at the other AWS sites. At each AWS site, the highest relative humidity was recorded in winter and the lowest during May, and the annual mean value of the relative humidity was always less than 50%. Little snowfall was observed during the winter and it is estimated that the value corresponded to about 10% of the precipitation recorded in local Mongolian routine observation reports. The commencement of freezing and melting/thawing of soil at all AWS sites was seen in October and March, respectively. Other AWS showed similar phenomena. Some of the fundamental physical parameters of the study area soils were obtained from short-term intensive field observation periods carried out during each of the summers.

2.3 Ground-based soil moisture measurement

We employed TDR (Time Domain Reflectometry) for the measurement of ground-based soil moisture in the study area. In particular, TDR soil moisture probes (TRIME IT, IMKO) with two 11 cm in length stainless rods of 3.5 mm in diameter were equipped with AWS and ASSH and were set horizontally in the study area. According to our laboratory tests, the effective measurement area of the employed TDR probe corresponded to the ellipsoid of about 7.5 cm in the major axis and 3 cm in the minor axis of the cross section and 11 cm in the longitudinal. That is, it measures vertically the volumetric water content in the soil from about 1.5 to 4.5 cm depths. Ideally, the ground-based soil moisture monitoring for AMSR-E validation should be done in a thin surface soil layer (0–1 cm depth soil layer). But, in the current, it is not so easy to monitor soil moisture in the thin soil surface.

All of the TDR soil moisture probes were tested for probe error by sampling and using an oven method using a PVC column and glass beads of 0.1 mm φ in the laboratory before installation. Figure 3 shows the results of the test. The relative accuracy of the TDR probes was within ±1.6% at a volumetric water content of 40%.

In the case where broken TDR probes were replaced, the new TDR probes were also tested following the above-mentioned procedure in order to maintain the same probe error and accuracy as the ongoing TDR probes.

2.4 Algorithm for standard product of soil moisture of AMSR-E

AMSR-E has been measuring the brightness temperature based on the following equation:

\[ T_b = \exp(-\tau_c) \cdot E_i \cdot T_s + \left[ 1 - \omega_c \right] \left[ 1 - \exp(-\tau_c) \right] T_e \]  

(1)

where \( T_b \) is the brightness temperature, \( T_s \) is the canopy physical temperature, \( \omega_c \) is the single scattering albedo of the canopy, \( \tau_c \) is the optical depth of the canopy, \( T_s \) is the soil physical temperature, and \( E_i \) is the soil emissivity. \( E_i \) is well known to depend mostly on soil moisture.

The brightness temperature in Eq. (1) is essentially dependent on four variables which are the plant water content \( (\theta_p) \), the soil moisture \( (SM) \), the vegetation temperature \( (T_v) \), and the soil surface temperature \( (T_s) \). It is extremely difficult to solve Eq. (1) without the elimination of these variables. So, Koike et al. proposed the original soil moisture index \( (ISW) \) and polarization index \( (PI) \) to obtain \( SM \) and \( \theta_p \) under the assumption that \( T_v \) equals \( T_s \) and the atmosphere and rain are transparent to the observed frequencies of the AMSR-E. \( ISW \) and \( PI \) were found to be, respectively, as follows:

\[ ISW = \frac{T_b_i - T_b_j}{\left( T_b_i + T_b_j \right) / 2} \]  

(2)

\[ PI = T_b_i - T_b_j / (T_b_i + T_b_j) / 2 \]  

(3)

where the subscript \( i \) denotes a high frequency, \( j \) denotes a low frequency, \( H \) a polarization, and \( V \) a polarization. \( ISW \) and \( PI \) depend on the soil water content change and the plant water content of the plant layer on the soil surface, respectively. By changing the soil moisture from 0 to 60% by volume and \( \theta_p \) from 0 to 2.0 Kg/m², a family of brightness temperatures was generated by the forward model using Eq. (1). Then, the brightness temperatures were used to calculate the corresponding values for the \( ISW \) and \( PI \). Finally, we developed a look-up table for the \( ISW-PI \) relationship. In order to calculate the soil moisture using the look-up table, the data set obtained by the NDVI is indispensable. Actually, the monthly mean NDVI data for 2000 with a resolution of 0.1 degree of NOAA AVHRR were used to obtain the standard product of the AMSR-E soil moisture estimation. Frequencies of 10.65 GHz and 36.5 GHz were employed for the calculation of the \( ISW \), and 10.65 GHz was used for the \( PI \). In this way, the standard product data (Ver. 5.0 of JAXA) was pro-
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Fig. 3 Error and accuracy test results of the TDR probes (SM : soil moisture).

duced and provided to the principal investigators of the ADEOS-II Research Project. The algorithm is described in detail by Lu et al.6

3. Results and Discussion

3.1 Ground-based soil moisture change

Figure 4 represents the ground-based monitoring results of the daily area soil moisture (SMarea) at a depth of 3 cm and the area precipitation averaged from all of the AWS precipitation records over the last six years (2002–2007). The data used are partly available at the CEOP website (http://www.ceop.net). Unfortunately, as Table 2 shows, the data conditions for the calculation of daily area soil moisture at a depth of 3 cm, some stations were not always able to perform ideally throughout the monitoring period because of electrical problems, etc. SMarea refers to the arithmetic mean of the daily mean soil moisture from all of the available stations as follows:

\[
SM_{\text{area}} = \frac{\sum (SM_{\text{AWS}} + \cdots + SM_{\text{ASSH}})}{N}
\]  

(4)

where N is the number of available AWS and ASSH stations, SM is the soil moisture, \(\Sigma\) is the summation from I = 1 to N, and n and m refer to the station name.

The daily area soil moisture varied widely and frequently, from between a few percent to about 21%. As rainfall occurred frequently in the period from April to August of each year, the soil moisture responded significantly to periods of rainfall, as shown by the spikes. During autumn and winter, the soil moisture varied significantly because of the low dielectric constant due to the frozen soil, but fluctuated widely and unexpectedly with the thawing of snowfall/freezing of soil during March. According to statistical analysis, there was a slight decline of the daily area soil moisture. As a result, although the data were available only during the period from late April to September, we were able to obtain a large amount of useful ground-truth data on soil moisture for the purpose of validating the AMSR-E algorithm.

We tried to average the soil moisture spatially at a depth of 3 cm for all AWS and ASSHs during the unfrozen soil period from May to September for the last six years (2002 to 2007), as shown in Fig. 5. Although the average the soil moisture in 2003 represented the highest value, the statistical calculation showed that it decreased over the last six years. This suggests that the surface soil has been drying in the study area.

Inter-comparison tests comparing existing TDR probes and a new one were carried out in 2006 and 2007, in order to investigate the actual accuracy and error change of the TDR probes over time in the study area soils. Two seven-year-old TDR probes were set to overlap, and each measurement area was compared with each other, and then compared at the same time for four months at the same point. Figures 6 and 7 represent the results. It is obvious that there is a good correlation and linearity between devices. This means that the ground-based soil moisture measurements taken in the study area are very accurate and that the probes are robust.
Fig. 5 Change of the yearly mean area soil moisture (SMarea) at the 3cm depth in the unfrozen soil period (May - September) from 2002 to 2007.

Fig. 6 Inter-comparison test results of an old TDR probe of ASSH6 and with a new TDR probe ASSH5N (Broken line : regression line, Test period : June–September in 2006).

3.2 Validations

We compared the daily monitoring data of ground-based soil moisture in the study area with the standard product data (Ver. 5.0) of soil moisture estimation by the AMSR-E algorithm, as mentioned before. As shown in Table 2, the number of available stations from May to August in 2004 is less than desirable. However, we were able to obtain data from more that thirteen stations per year in other years. For the estimation of AMSR-E soil moisture, we sampled in a practical way the brightness temperature in areas of 5 by 6 pixels (1 pixel is 0.25°), covering perfectly the ground-based study area. The soil moisture estimation of AMSR-E was obtained by averaging arithmetically the summation of the AMSR-E soil moisture calculation value in each pixel.

Figure 8 represents the validation results of the comparison. In this figure, on the whole, good timing was observed in the response pattern, and the difference between the AMSR-E soil moisture estimation and the ground-based area soil moisture by Eq. (4) is small. However, in 2007, in the low soil moisture range of less than 5% (in spring), there is a remarkable difference between the AMSR-E soil moisture estimation and the ground-based area soil moisture. On the other hand, in the soil moisture range of about 7% (in summer), we can see a relatively good agreement. In spite of observing no soil moisture can be observed throughout the year. As the AMSR-E soil moisture responds to rainfall events, this can be considered to be caused by wet conditions in the thin surface soil layer and/or in the vegetation layer due to small amounts of rainfall. This disagreement leads to an influence on a relationship between the AMSR-E soil moisture estimation and the ground-based soil moisture, as will be discussed later.

Figure 9 shows the relationship between the AMSR-E soil moisture estimation and the ground-based soil moisture in each year from 2002 to 2007. At a glance, as plots are seen to scatter mostly near the 1:1 line and the AMSR-E soil moisture estimation varies with the ground-based soil moisture in each year, the relationships can be considered to be useful. Furthermore, although some significant overestimates of more than about 10% can be observed in the plots in the higher soil moisture range, and smaller overestimates in the lower range of less than 10%, we found an adequate correla-
Validation results from 2002 to 2007 (○: Ground-based daily mean SMarea by Eq. (4), □: AMSR-E SM of descending, △: area precipitation Parea (mm/d), SM: soil moisture).
Fig. 9 Relationships between daily mean estimation of AMSR-E SM and Ground-based SM of daily mean (Broken line : regression line).
tion between the AMSR-E estimation and the ground-based soil moisture. Table 3, showing the results of the regression analysis of the relationships is evidence of this. The AMSR-E overestimates can be estimated to depend on the depth of the ground-based soil moisture monitoring. If the soil moisture measurement is done at the shallower depth more than 3 cm depth, the overestimates could decrease more.

Unfortunately, the number of the data points in the AMSR-E soil moisture estimation is insufficient for statistical analysis because of the launch of AQUA in May, 2002. Therefore, the AVE in 2002 are not calculated precisely.

The AVE was determined as follows:

\[
AVE = \frac{1}{n} \sum |\theta_{\text{AMSR-E}} - \theta_{\text{ground-based}}|
\]

where AVE is the average absolute error, the values of \( n \) are 1, 2, ..., and \( \sum \) is the summation from \( i=1 \) to \( n \).

All AVE values, except that in 2007, are not larger and better than expected. The highest AVE value was found in 2007, implying that the validation results in 2007 are poor compared with other years, as discussed in Fig. 8. Although there are plausible explanations for this, it is worth noting that the measurement depth change\(^9\) of the AMSR-E with the surface soil drying is the primary reason. However, it is important to investigate also a calibration accuracy of AMSR-E itself in the near future. Consequently, there is a high possibility that the AMSR-E detected soil moisture at a depth of deeper than 3 cm. As mentioned in Section 2.2, the driest surface condition occurred in 2007. This is evidence for this hypothesis.

3.3 AMSR-E soil moisture estimation over a large area

An attempt was made to construct a map of the AMSR-E soil moisture estimation over a large area. Figure 10 gives a few sample maps for Mongolia and its surrounding countries using the standard product data of the AMSR-E soil moisture estimation based on the last ten days in each month from late June to late September, 2003. The distribution change of the AMSR-E soil moisture estimation with month is remarkable. Namely, the soil moisture in Mongolia increases steadily from June to July (the rainy season) and then decreases toward September with decreasing precipitation. In particular, the change is easily seen in central-western Mongolia (Tuul river basin) and in the northern part of China.

The distribution pattern in Mongolia is very similar to that of the precipitation\(^10\). The masked parts (gray-colored pixels), which mean that the calculated results are beyond the limits of calculation conditions, are mainly seen in the northern area of Mongolia and Siberia, which consist of forest and dense vegetation. However, some can be seen in the steppe and in the desert area, and also in the study area, where there is sparse vegetation. The reason for this is not obvious, but it may be due to the lack of accurate NDVI data for use in the look-up table of the ISW-P1 relationship.

4. Conclusions

The results of this study are summarized as follows:

1) The ground-based monitoring of soil moisture and some water cycle elements in the study area of the Mongolian Plateau have been successfully carried out and provided a large amount of reliable data on soil moisture since 2001 for satellite validation.

2) Although the standard product (Ver. 5.0 of JAXA) using the soil moisture algorithm of AMSR-E slightly overestimated the soil moisture, the validation results were good and there was a good correlation between the AMSR-E soil moisture product and the long-term ground-based soil moisture monitoring.

3) The standard product of the AMSR-E soil moisture estimation gave a reasonable match between the change and distribution of soil moisture in Mongolia.

In conclusion, the quality of the standard product of the AMSR-E soil moisture estimation was good and found to be useful for surface soil moisture monitoring over a large scale.

However, unfortunately, the representativeness of the ground-based soil moisture data at each station was not discussed in this paper. It is very important to check the representativeness, as the spatial variability within a single pixel can affect the interpretation of remote-sensed soil moisture data\(^11\). To establish the soil moisture measurement algorithm of AMSR-E and AMSR2 (Advanced Microwave Scanning Radiometer-2) of a new satellite (GCOM-W1 : Global Change Observation Mission-Water 1) which will be launched in Japanese fiscal year 2011, it will be necessary somehow to take on the challenge of studying the representativeness and to get a feel for the real soil moisture distribution conditions within an AMSR-E pixel. Possible candidates include the PALSAR (Phased Array type L-band Synthetic Aperture Radar) of ALOS (Advanced Land Observing Satellite) in addition to ground-based observations.
Fig. 10 Distribution change of the ten day mean soil moisture estimation in Mongolia by AMSR-E (2003) with month (□: study area).
Furthermore, there is a high possibility that the investigation of the ground-based soil moisture monitoring depth could bring the decrease of AMSR-E overestimates. A new technology to measure soil moisture in a thin soil layer near the surface would be expected as challenged by a few scientists[2]. The data of ground-based monitoring of soil moisture in the study area are partly opened to all researchers at the CEOP website (www.ceop.net).

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