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First Assessment of the Advanced Microwave Scanning Radiometer 2 (AMSR2) Soil Moisture Contents in Northeast Asia

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Abstract

The Advanced Microwave Scanning Radiometer 2 (AMSR2) onboard the Global Change Observation Mission 1–Water (GCOM-W1) was launched by the Japan Aerospace Exploration Agency (JAXA) in May 2012. The AMSR2 is the follow-on model of the AMSR-Earth Observing System (AMSR-E) onboard the Aqua satellite. An assessment of the reliability of the soil moisture estimations from the newly launched passive sensor, the AMSR2, was carried out in this study, by using in situ soil moisture data from nine locations on the Korean peninsula during the period from July to October, 2012. The temporal patterns of the AMSR2 had a rough association with the in situ soil moisture measurements. However, there was intermittent striking of the AMSR2 data, in comparison to the in situ time series. For a clearer comparison between the variables, normalizing and filtering methods were applied to the AMSR2 soil moisture data with less systematic differences. The error estimation was based on triple collocation, and the AMSR2 data showed a larger error than the in situ and Global Land Data Assimilation System (GLDAS) soil moisture values. The spatial distributions of the monthly AMSR2 soil moisture were analyzed from the perspective of the corresponding reaction of the soil moisture to the spatial distributions of precipitation. The results provided an overview of the AMSR2 soil moisture product that is useful, despite being somewhat limited over the regions in northeast Asia. This study offers an insight into the applicability of the soil moisture products derived from the AMSR2 sensor. However, further studies are required for better understanding of the AMSR2 products for other areas of the validation task.

Keywords soil moisture; AMSR2; precipitation; remote sensing; validation

1. Introduction

Over the past few decades, microwave sensor systems have been preferentially used to measure fresh and salt water on the Earth's surface because they have major advantages such as a deep penetra-

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tion capacity and direct measurements in all weather conditions (Jackson and Schmugge 1995). Various passive and active sensors in microwave sensor systems have been employed since 1973 (Schmugge et al. 2002; Bolten et al. 2003). Since the first passive microwave sensor, the Skylab S-194 radiometer (1973–1977), the Advanced Microwave Scanning Radiometer E (AMSR-E: 2002–2011) sensor has recently been used to provide regional surface soil moisture measurements on a global scale. As with passive microwave sensors, various active microwave sensors have also been used since 2006, such as Scatterometers , and the Advanced Scatterometer (ASCAT).

In contrast to the major advantages of microwave sensor systems, there have also been several unavoidable limitations: less sensitivity in vegetated regions, coarse spatial resolutions, and only shallow soil moisture measurement depths (Jackson et al. 2010; Mladenova et al. 2010; Choi 2012; Leroux et al. 2013). Due to these unavoidable limitations, intensive remotely sensed soil moisture validation efforts have been conducted for major passive and active microwave sensor systems. A few samples of recent validation studies are Draper et al. (2009), Mladenova et al. (2011), Brocca et al. (2012), Choi (2012), Su et al. (2013), Wagner et al. (2013), Leroux et al. (2013), and Fang and Lakshmi (2014).

Compared with other passive microwave sensors, four soil moisture retrieval products, based on different algorithms, were developed and validated for the AMSR-E sensor, which is one of the most widely used passive microwave systems. However, the antenna on the AMSR-E sensor recently stopped, and data have not been provided since October 2011. Until its demise, the AMSR-E sensor successfully provided global soil moisture products on a daily basis. In order to continue its successful role in observing biophysical variables, including brightness temperature, the Advanced Microwave Scanning Radiometer 2 (AMSR2) on the Global Change Observation Mission 1–Water (GCOM–W1) was launched by the Japan Aerospace Exploration Agency (JAXA) in May 2012. The AMSR2 shows several improved characterizations (Imaoka et al. 2010): an improved thermal design for high temperature noise source , a larger main reflector with a 2 m diameter for better spatial resolution, and new dual polarization channels at 7.3 GHz, in order to identify and remove intensive radio frequency interference signals, which were frequently observed at 6.9 GHz on AMSR and AMSR-E.

In this study, we aimed to evaluate/validate the AMSR2 soil moisture products during the first growing season after launch (May to September in 2012) in the Korean peninsula. Appropriate validations were required to be established in different climatic zones and meteorological conditions even though the AMSR2 soil moisture content (SMC) will have been further reprocessed along with the correction of brightness temperature (the latest version of SMC is 1.1, updated on September 25, 2013). The meteorological and vegetative characteristics of South Korea are significantly different from those of the validation sites in some of the previous studies of the AMSR2 soil moisture validation (Yee et al. 2013; Kachi et al. 2013), which could possibly contribute to the improvement of the algorithm by enhancing the diversity of the validation sites.

2. Description of the study area and ground-based measurements

The Korean peninsula enjoys a temperate humid climate. The average annual precipitation is 1,338 mm, and the heaviest rainfall generally occurs during the summer season because of the East Asian monsoon (KMA 2012). In 2012, the annual precipitation ranged from 1,046 to 1,391 mm, and the precipitation during this study period (July 3–October 31) ranged from 691 to 1,269 mm. The air temperature during this period ranged from 17.3°C to 22.3°C. These data were provided by the Korean agricultural meteorological information service (http://weather.rda.go.kr).

In situ measurements of SMCs are necessary to assess remotely sensed soil moisture products. The Rural Development Administration (RDA) network, located in the southern sector of the Korean peninsula, was installed by the RDA (http://rda.go.kr) for agricultural meteorological purposes related to the understanding of the direct and indirect influence of the near surface and root zone soil moisture on the growth of crops. Since 2000, a network of ground-based soil moisture stations has been set up over this area. The CS615 or CS616 water content reflectometers, and time domain reflectometry sensors were installed over all of the RDA sites (Campbell Scientific Inc. 1996, 2012). For this study, in situ soil moisture data were collected from 0 to 10 cm. One point to consider is the unavoidable limitation of the difference in the measurement depth with microwave satellite data (Jackson et al. 2010). The principal soil textures on the surface were loam and sandy loam (Korean Soil Information System, http://soil.rda.go.kr). The dominant land use was agriculture and rice was the major crop (59 %).

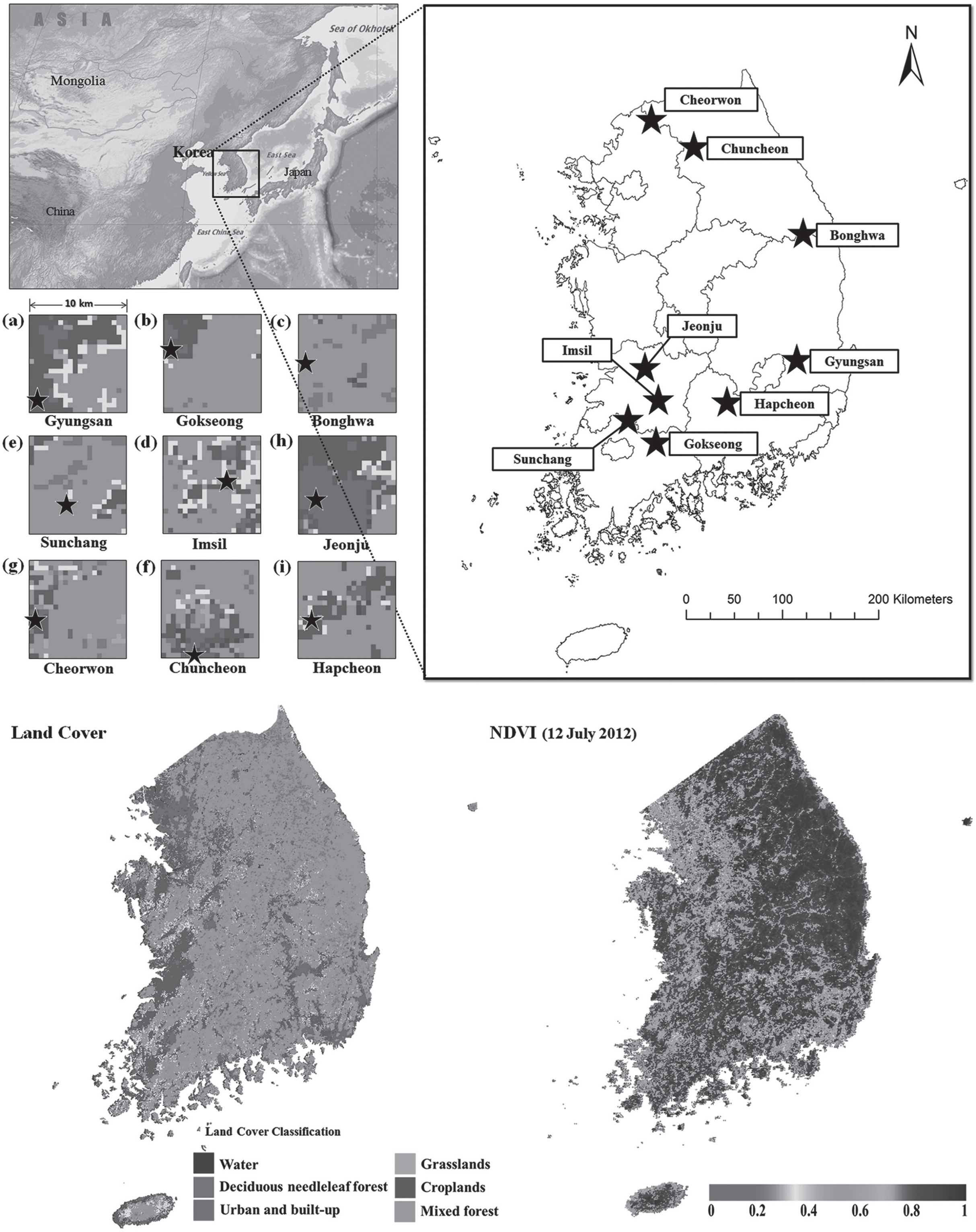

Fig. 1. Validation sites in the Korean peninsula (each star mark indicates the location of the sites).

Table 1. The characteristics of the study areas.

Area	Latitude (degree)	Longitude (degree)	Elevation (m a.s.l)	Annual rainfall (mm)	Temperature (°C)	Relative humidity (%)	Land cover
Gyeongsan	38°16′N	126°59′E	58 m	1046.8	12.4	65.1	Crop land
Gokseong	35°15′N	127°18′E	60 m	1391.0	13.8	69.5	Crop land
Bonghwa	37°03′N	129°00′E	636 m	1217.9	9.9	69.3	Mixed forest
Sunchang	35°26′N	127°02′E	253 m	1380.4	12.3	71.7	Mixed forest
Imsil	35°39′N	127°16′E	256 m	1351.9	11.2	73.3	Mixed forest
Jeonju	35°50′N	127°06′E	41 m	1313.1	13.3	69.4	Urban
Cheorwon	38°08′N	127°18′E	156 m	1347.3	11.1	71.0	Crop land
Chuncheon	37°54′N	127°44′E	79 m	1391.2	10.2	70.4	Urban
Hapcheon	35°32′N	128°06′E	44 m	1275.6	13.0	67.6	Crop land

In this study, the nine sites of Gokseong, Gyeongsan, Bonghwa, Sunchang, Imsil, Jeonju, Cheorwon, Chuncheon, and Hapcheon were selected for validation (Fig. 1). Table 1 indicates the characteristics of each station, such as the locational (latitude, longitude, and elevation), meteorological (mean annual rainfall, temperature, and relative humidity), and physical (soil texture and land use) information.

3. AMSR2 and Global Land Data Assimilation System (GLDAS) data

3.1 AMSR2 SMC

The AMSR2 on board the GCOM-W1 was launched on May 18, 2012, and began its scientific observations on July 3, 2012. The available soil moisture product was provided by the JAXA Earth Observation Research Center (EORC) every 1 to 2 days, from both the ascending (13:30 local time) and descending (01:30 local time) overpasses. The spatial resolution of the SMC products was of 10 km and 25 km scales. These data are available for download from https://gcom-w1.jaxa.jp/. In this study, we used the SMC product version 1.0.

The AMSR2 soil moisture product was derived from the radiative transfer model (RTM) of the soil surface–vegetation layer (Koike 2013). The RTM is available for cases in which the satellite footprint scale is uniformly covered with vegetation. However, in actuality, uniform vegetation cover exists in only a few regions globally (Koike et al. 2004; Fujii et al. 2009).

In order to allow simultaneous retrieval of the soil moisture and vegetation water content, the polarization index (PI) and index of soil wetness were calculated. These indices were calculated because the vegetation water content influences the sensitivity of the microwave SMCs. These indices represent the polarization and frequency differences, respectively, divided by the mean value of the brightness temperature, expressed as follows:

$$\text{Index of Soil Wetness} = \frac{T_{B(36Hz),H} - T_{B(10Hz),H}}{\frac{1}{2}\left(T_{B(36Hz),H} + T_{B(10Hz),H}\right)} \tag{1}$$

and

$$\text{Polarization Index} = \frac{T_{B(10Hz),V} - T_{B(10Hz),H}}{\frac{1}{2}\left(T_{B(10Hz),V} + T_{B(10Hz),H}\right)} \tag{2}$$

where, $T_{B,H}$ is the microwave brightness temperatures of the horizontal polarization, and $T_{B,V}$ is the microwave brightness temperatures of the vertical polarization, with high (36 Hz) or low (10 Hz) frequencies, respectively.

Lookup tables were used as inverse analysis tables, when retrieving the soil moisture and vegetation water content from the microwave brightness temperatures (Fujii et al. 2009). In this study, the 10 km spatial scale soil moisture products were used to compare with the ground measurements at the nine stations in Korea.

3.2 GLDAS soil moisture

The GLDAS was developed for the purpose of obtaining near-real time estimation of the land surface states and fluxes with high-resolution and optimized accuracy (Rodell et al. 2004). The GLDAS uses the land surface models (LSMs) with observation-based meteorological fields as forcing. The three-hourly 0.25° GLDAS version 1 products used in this study were derived solely by Noah, since such spatio-temporal resolution is not available from other LSMs in GLDAS. The soil moisture was an averaged value from the 0–10cm depth from the surface. More detailed information on GLDAS SMC is available in Rodell et al (2004).

3.3 Triple collocation (TC)

The triple collocation method applied to soil moisture estimates the systematic errors from each of three collocated datasets and allows cross-calibration under the condition that the errors from the three sources are not correlated (Stoffelen 1998; Scipal et al. 2008; Dorigo et al. 2010). The method adopted in this study was specifically related to the work of Miralles et al. (2010), which estimated the spatial sampling uncertainty of the coarse-scale soil moisture datasets (remote sensing and land surface modeling) derived from the point-scale observations.

Each soil moisture observation can be decomposed into its climatology mean and anomaly components as follows:

$$\theta_i = \theta_i' + \langle \theta \rangle_{t(i)}^{N} \tag{3}$$

where $\langle \theta \rangle_{t(i)}^{N}$ is the climatological expectation at the specific time (t) with given time step (i), which were calculated in this study through moving window averaging of 62 time steps (31 days) centered on t, and θ_i' is the actual anomaly relative to the expectation.

The difference between the temporal anomalies of the remotely sensed soil moisture and the point-scale ground observation is as follows:

$$\begin{aligned} &\theta_{RS}' - \theta_{POINT}' = \\ &\quad (\theta_{RS}' - \theta_{TRUE}') + (\theta_{TRUE}' - \theta_{POINT}') \end{aligned} \tag{4}$$

where θ_{TRUE}' represents the true anomaly. Under the assumption that the error from each source is mutually independent, the mean square of both sides of Eq. (4) can be rewritten in terms of the error from the remote sensing observation as follows:

$$\begin{aligned} &\mathrm{MSD}\,(\theta_{RS}', \theta_{TRUE}') = \\ &\quad MSD\,(\theta_{RS}', \theta_{POINT}') - MSD\,(\theta_{POINT}', \theta_{TRUE}') \end{aligned} \tag{5}$$

where MSD is the mean-square differences of the two components. The anomaly and MSD of the LSM can be written in the same structure as Eqs. (4) and (5).

Based on the relationship between the temporal anomaly of each soil moisture estimate and the true soil moisture anomaly, as well as the mutual independency among systematic errors, the spatial sampling error of the point-scale observation can be expressed as follows:

$$\begin{aligned} &\langle (\theta_{POINT}' - \theta_{RS}')\,(\theta_{POINT}' - \theta_{LSM}') \rangle = \\ &\quad \langle \varepsilon_{POINT}^2 \rangle = MSD\,(\theta_{POINT}', \theta_{TRUE}') \end{aligned} \tag{6}$$

where $\langle\ \rangle$ indicates an averaging in time. The errors of the remotely sensed and LSM estimates of the soil moisture can then be calculated using Eqs. (5) and (6). A more detailed explanation of TC is available in Miralles et al. (2010) and Scipal et al. (2008).

4. Results and discussion

4.1 Validation of the AMSR2 soil moisture

We evaluated the AMSR2 soil moisture retrievals with in situ observations located on the Korean peninsula in 2012. The time series plots in Fig. 2 show that there were considerable differences between the AMSR2 and the in situ data sets with intermittently striking fluctuations, while the GLDAS data set well followed the temporal trend of the in situ soil moisture. In particular, the AMSR2 time series showed extreme values when precipitation events occurred occasionally. These results could be caused by various factors such as mismatches of spatial scale and measuring depth between the AMSR2 and in situ measurement. In addition, it can be considered that the retrieval of the AMSR2 SMC is on processing along with the correction of the brightness temperature.

Figure 2 also shows that the AMSR2 products were generally underestimated over the entire period except for spiking intermittently. The values ranged from 0.09 to 0.14 $\mathrm{m^3\ m^{-3}}$, and the standard deviations of the soil moisture ranged from 0.08 to 0.14 $\mathrm{m^3\ m^{-3}}$. This low temporal variability with underestimated patterns of the AMSR2 soil moisture was similar to those of the National Snow and Ice Data Center (NSIDC) AMSR-E soil moisture products, which were found in several NSIDC AMSR-E validation studies (Wagner et al. 2007; Gruhier et al. 2008; Jackson et al. 2010; Choi et al. 2008; Choi 2012).

Table 3 indicates that the correlation (R), bias, absolute mean error (AME), and root mean square error (RMSE) were calculated between the AMSR2, and the (a) in situ and (b) GLDAS data sets. Among the AMSR2 standard products, the accuracy of the SMC product was defined as AME (EORC 2013) and the required validation and release accuracy is 0.10 $\mathrm{m^3\ m^{-3}}$. In this study, the AME between AMSR2 SMC and in situ observation was 0.13 $\mathrm{m^3\ m^{-3}}$, which almost satisfies the required accuracy. The R-values between the original AMSR2 products and the ground-based measurement values ranged from 0.10 to 0.47 (Average = 0.31). Table 3 shows that the biases ranged from 0.02 to 0.18 $\mathrm{m^3\ m^{-3}}$ (Average = 0.09), and the RMSE ranged from 0.10 to 0.21 $\mathrm{m^3\ m^{-3}}$ (Average = 0.15). The AMSR2 soil moisture products presented a relatively poor correlation with the in situ

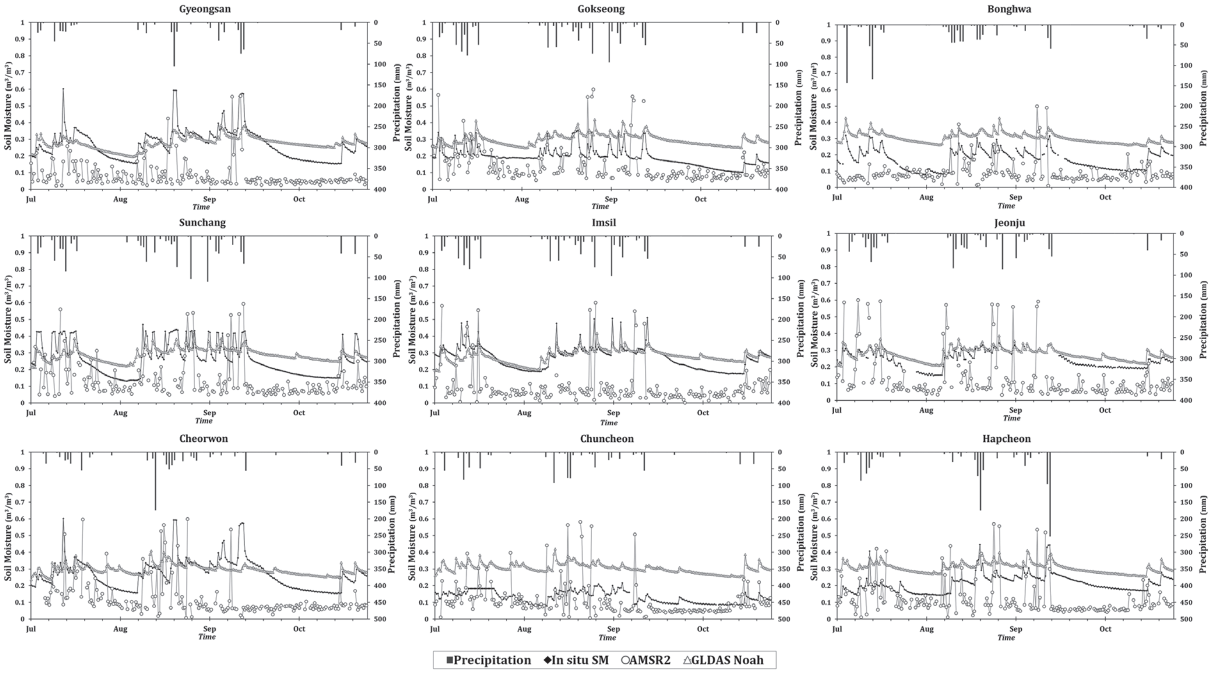

Fig. 2. Time series of the precipitation, AMSR2, and in situ soil moisture products.

Table 2. Statistics of the AMSR2 (Original) with the in situ soil moisture data according to the overpass time (descending / ascending).

Stations	Descending (m^3 m^{-3})					Ascending (m^3 m^{-3})				
	Average	Stdev	r	AME	RMSE	Average	Stdev	r	AME	RMSE
Gyeongsan	0.06	0.04	0.44	0.03	0.22	0.12	0.10	0.45	0.16	0.18
Gokseong	0.14	0.11	0.40	0.09	0.12	0.14	0.11	0.54	0.08	0.10
Bonghwa	0.10	0.08	0.29	0.09	0.11	0.10	0.07	0.21	0.08	0.10
Sunchang	0.13	0.1	0.43	0.14	0.16	0.15	0.12	0.28	0.15	0.17
Imsil	0.14	0.14	0.34	0.19	0.2	0.07	0.07	0.24	0.20	0.21
Jeonju	0.15	0.15	0.36	0.15	0.19	0.12	0.13	0.27	0.16	0.18
Cheorwon	0.13	0.12	0.32	0.09	0.11	0.12	0.10	0.41	0.09	0.11
Chuncheon	0.10	0.10	0.28	0.07	0.10	0.11	0.10	0.22	0.07	0.10
Hapcheon	0.11	0.10	0.24	0.13	0.14	0.14	0.11	0.29	0.11	0.13
Total	**0.12**	**0.10**	**0.34**	**0.12**	**0.15**	**0.12**	**0.10**	**0.32**	**0.12**	**0.14**

data at some of the sites. In particular, these products underestimated the values during the overall period and were not found to correspond with the rainfall events, which are shown in Fig. 2. These results show patterns similar to the initial results obtained from the AMSR2 validation with the in situ soil moisture data from the Little River Experimental Watershed in Georgia in the United States (EORC 2013). These results may be caused by two valid reasons. The first reason is that the climate conditions of this area were similar to that of the Korean peninsula, where rainfall events occurred frequently in the summer season. The annual precipitation in Georgia is approximately 1,200 mm. Precipitation typically occurs as high intensity rainfall events in both regions during the summer season, with relatively small spatial extents (Bosch et al. 1999, 2006). The second reason may be the similar surface and soil characteristics, such as

Table 3. Statistics of the AMSR2 (Original) with (a) in situ and (b) GLDAS soil moisture data.

	(a) In situ soil moisture (m^3 m^{-3})						(b) GLDAS soil moisture (m^3 m^{-3})					
Stations	Average	Stdev	r	AME	Bias	RMSE	Average	Stdev	r	AME	Bias	RMSE
Gyeongsan	0.11	0.09	0.41	0.17	0.16	0.19	0.28	0.04	0.15	0.20	0.19	0.21
Gokseong	0.14	0.11	0.47	0.09	0.05	0.11	0.30	0.03	0.28	0.18	0.16	0.19
Bonghwa	0.09	0.08	0.22	0.10	0.07	0.12	0.31	0.03	0.18	0.22	0.21	0.22
Sunchang	0.14	0.11	0.29	0.15	0.12	0.17	0.29	0.04	0.23	0.17	0.15	0.19
Imsil	0.10	0.11	0.33	0.19	0.18	0.21	0.28	0.04	0.17	0.21	0.19	0.22
Jeonju	0.13	0.14	0.31	0.16	0.06	0.18	0.28	0.04	0.29	0.19	0.14	0.20
Cheorwon	0.13	0.11	0.35	0.09	0.05	0.11	0.30	0.03	0.39	0.19	0.17	0.20
Chuncheon	0.11	0.10	0.28	0.07	0.02	0.10	0.31	0.03	0.34	0.21	0.20	0.22
Hapcheon	0.12	0.10	0.10	0.12	0.09	0.14	0.31	0.03	0.40	0.20	0.19	0.21
Total	**0.12**	**0.11**	**0.31**	**0.13**	**0.09**	**0.15**	**0.30**	**0.03**	**0.27**	**0.20**	**0.18**	**0.21**

the dense vegetation and soil texture in the research area (Bosch et al. 1999; Cho and Choi 2014). It seems that the AMSR2 data sets also have the limitation of passive microwave sensors operating in heavily vegetated conditions (Njoku et al. 2003; Choi 2012; EORC 2013).

Generally, the descending (night-time) microwave satellite data was expected to obtain more accurate SMCs than the ascending pass, since the surface brightness temperature was more homogenous at the descending pass time (01:30). Through several previous studies of the AMSR-E, the descending (night-time) pass was considered to detect more accurate values than the ascending (day-time) pass (Draper et al. 2009). In the obtained results, a similar tendency was seen, although it shows poor correlation for the nine sites. Through the data in Table 2, we perceived that the two datasets obtained for the ascending and descending data did not indicate significant differences. The R-values of the original satellite datasets were in the ranges from 0.24 to 0.44, and from 0.21 to 0.54, with average values of 0.34 and 0.32 for the ascending and descending AMSR2 soil moisture datasets, respectively.

The obtained results were worth comparing with the previous validation tests in the EORC (2013) and by Kachi et al. (2013). These studies initially validated the AMSR2 soil moisture products by comparison with ground-based measurements, measured at campaign sites in the United States, Mongolia, Thailand, and Australia. Unlike the U.S. Little River region, as mentioned before, the validation results for the other sites showed relatively reasonable agreement between the in situ measurement and the satellite-based SMCs. This result is due to the fact that these nations' validation sites had relatively homogeneous land cover and numerous sampling points in the AMSR2 remote-sensing footprint. However, the in situ data measured at the RDA sites and the U.S. Little River site were not averaged values of multiple points, but just point measurement values. In particular, the RDA sites in Korea were not initially designed for the primary validation objective of the satellite-based data (Choi and Hur 2012).

4.2 *Normalization and filtering of the AMSR2 soil moisture*

In order to accurately compare two time series from remote sensing and ground-based measurements of soil moisture, we applied the average-standard matching method to eliminate the systematic differences that prevented an absolute agreement using the following Eq. (7) (Reichle et al. 2004; Draper et al. 2009; Brocca et al. 2011):

$$\hat{\vartheta}_s = \frac{\sigma_i}{\sigma_s}(\vartheta_s - \mu_s) + \mu_i \tag{7}$$

where $\hat{\vartheta}_s$ = normalized satellite data, μ_i = averages of in situ data, σ_i = standard deviations of in situ data, σ_s = standard deviations of satellite data, ϑ_s = original satellite data, and μ_s = averages of satellite data. In addition, the AMSR2 data was applied to a moving average filter (six-day) in order to reduce the noise prior to the normalization (Draper et al. 2009).

The time series graphs of the ascending, descending, and combined AMSR2 (filtered and normalized) soil moisture products with the in situ measurements are given in Fig. 3. These products indicated that the temporal variations for 2012 showed reasonable agreement with the precipitation events for the nine RDA sites. We determined significant improvements in the temporal patterns of

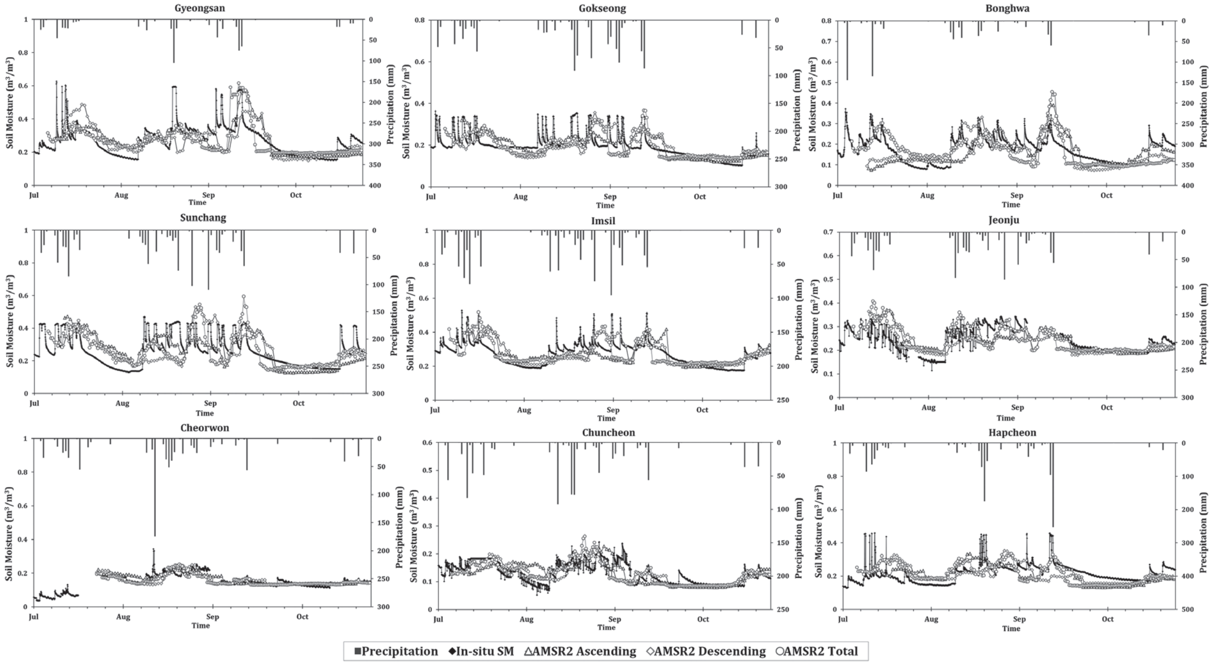

Fig. 3. Soil moisture from the ascending, descending, and total pass AMSR2 (filtered and normalized) with in situ products.

the AMSR2 remotely sensed products, through the filtering and normalization processes. These improvements included the removal of extremely high values or more underestimated data in contrast with the original AMSR2 products shown in Fig. 2. We determined the temporal variations between the descending and ascending AMSR2 SMCs shown in Fig. 3. There were no distinct differences in the two temporal patterns during the study period. Both of the time series generally responded to the rainfall events according to the precipitation intensity, unlike the original AMSR2 soil moisture time series. They also showed more improved agreement with the in situ measurements than that of the original AMSR2 soil moisture products. This result may imply that the original AMSR2 SMCs need a process for eliminating noise and systematic error. These results corresponded with the results of a previous study of the AMSR-E soil moisture (Draper et al. 2009).

Table 4 displays the results of the statistical index comparisons of the modified AMSR2 soil moisture products (through the filtered and normalized approach) for the descending and ascending pass, respectively. The average R-values were equal to 0.50 and 0.58 for the descending and ascending products, respectively. The AME (RMSE) values were also equal to 0.05 and 0.05 m^3 m^{-3} (0.06 and 0.06 m^3 m^{-3}) for all of the sites. In order to consider the entire products (both descending and ascending data), the R-values between the modified AMSR2 products and the in situ measurements ranged from 0.27 to 0.73 (Average = 0.55), and the AME ranged from 0.02 to 0.07 m^3 m^{-3} (Average = 0.04 m^3 m^{-3}) as shown in Table 5. This result somewhat satisfies the required validation accuracy (4%). The RMSE for the AMSR2 (filtered and normalized) products ranged from 0.02 to 0.10 m^3 m^{-3} (Average = 0.06 m^3 m^{-3}) when compared to the in situ data, which also met the target accuracy of the mission.

The TC method was applied in order to estimate the systematic error of the AMSR2 soil moisture taking into consideration the in situ and GLDAS soil moisture as references. The TC method provided an effective technique to investigate the satellite based soil moisture validation (Scipal et al. 2008; Dorigo et al. 2010). Figure 4 shows the estimated errors of the in situ, AMSR2, and GLDAS soil moisture with theoretically true soil moisture at each site. In general, the error of the AMSR2 (red) was found to be greater than the other two soil moisture data sets. This tendency is consistent with the results of the previous studies by Miralles et al. (2010) and Loew and Schlenz (2011)

Table 4. Statistics of the AMSR2 (filtered and normalized) with the in situ soil moisture data according to the overpass time (descending / ascending).

Stations	Descending ($m^3 m^{-3}$)					Ascending ($m^3 m^{-3}$)				
	Average	Stdev	r	AME	RMSE	Average	Stdev	r	AME	RMSE
Gyeongsan	0.27	0.09	0.56	0.06	0.08	0.27	0.09	0.62	0.06	0.08
Gokseong	0.19	0.05	0.42	0.04	0.05	0.20	0.05	0.65	0.03	0.05
Bonghwa	0.16	0.07	0.41	0.06	0.08	0.16	0.07	0.35	0.05	0.08
Sunchang	0.26	0.10	0.39	0.08	0.10	0.26	0.10	0.57	0.07	0.09
Imsil	0.28	0.07	0.62	0.04	0.06	0.27	0.06	0.61	0.05	0.06
Jeonju	0.24	0.05	0.59	0.08	0.04	0.24	0.05	0.62	0.07	0.04
Cheorwon	0.16	0.03	0.66	0.02	0.02	0.16	0.03	0.76	0.02	0.02
Chuncheon	0.13	0.04	0.66	0.02	0.03	0.13	0.04	0.60	0.03	0.04
Hapcheon	0.21	0.05	0.17	0.05	0.06	0.21	0.06	0.48	0.05	0.06
Total	**0.21**	**0.06**	**0.50**	**0.05**	**0.06**	**0.21**	**0.06**	**0.58**	**0.05**	**0.06**

Table 5. Statistics of the fit between the AMSR2 (filtered and normalized) and the in situ soil moisture measurements ($m^3 m^{-3}$).

Stations	Average	Stdev	r	AME	Bias	RMSE
Gyeongsan	0.27	0.09	0.59	0.06	0.00	0.08
Gokseong	0.19	0.06	0.53	0.04	0.00	0.05
Bonghwa	0.16	0.07	0.38	0.06	0.00	0.08
Sunchang	0.26	0.10	0.51	0.07	0.00	0.10
Imsil	0.27	0.07	0.57	0.05	0.00	0.06
Jeonju	0.24	0.05	0.64	0.03	0.00	0.04
Cheorwon	0.16	0.03	0.73	0.02	0.01	0.02
Chuncheon	0.13	0.04	0.68	0.02	0.00	0.03
Hapcheon	0.21	0.05	0.27	0.05	0.00	0.07
Total	**0.21**	**0.06**	**0.55**	**0.04**	**0.00**	**0.06**

targeting the estimation of AMSR-E products. In particular, Loew and Schlenz (2011) demostrated that the error (root mean square deviation) of the satellite (AMSR-E) was estimated to be generally larger than those of the LSM and ground based soil moisture. In addition, this figure indicates that the error of the GLDAS data (average: 0.03 $m^3 m^{-3}$) was slightly lower than that of the in situ data (average: 0.05 $m^3 m^{-3}$). This result indicated that the error of in situ soil moisture may be due to the spatial sampling errors associated with using sparse in situ soil moisture data (Loew and Schlenz, 2011). Considering that the AMSR2 calibration is ongoing, the reliability of the AMSR2 soil moisture products would be improved more according to the continuous data processing.

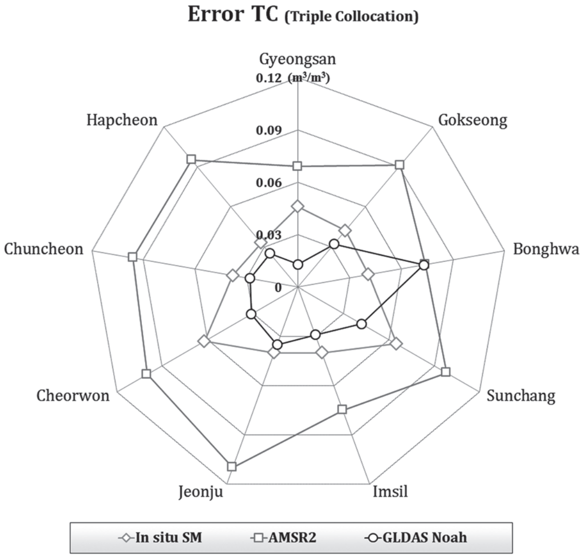

Fig. 4. Estimated errors of the soil moisture dataset from each source estimated by the TC.

4.3 AMSR2 soil moisture spatial distributions

The spatial distribution of the soil moisture anomaly was compared with the spatial distribution of the precipitation and vegetation. Figure 5 shows the responses of the soil moisture to precipitation on a monthly basis. Figure 5a indicates the anomaly of the monthly mean soil moisture, which used the average soil moisture during the studied period (July 2012 to October 2012) as reference data, and (b) shows the precipitation mappings that were obtained from the Tropical Rainfall Measuring Mission (TRMM) 3B43. The monthly precipitation products are presented with a 0.25° × 0.25° spatial resolution.

Overall, the spatial distribution of the AMSR2 soil moisture anomaly and precipitation were found to

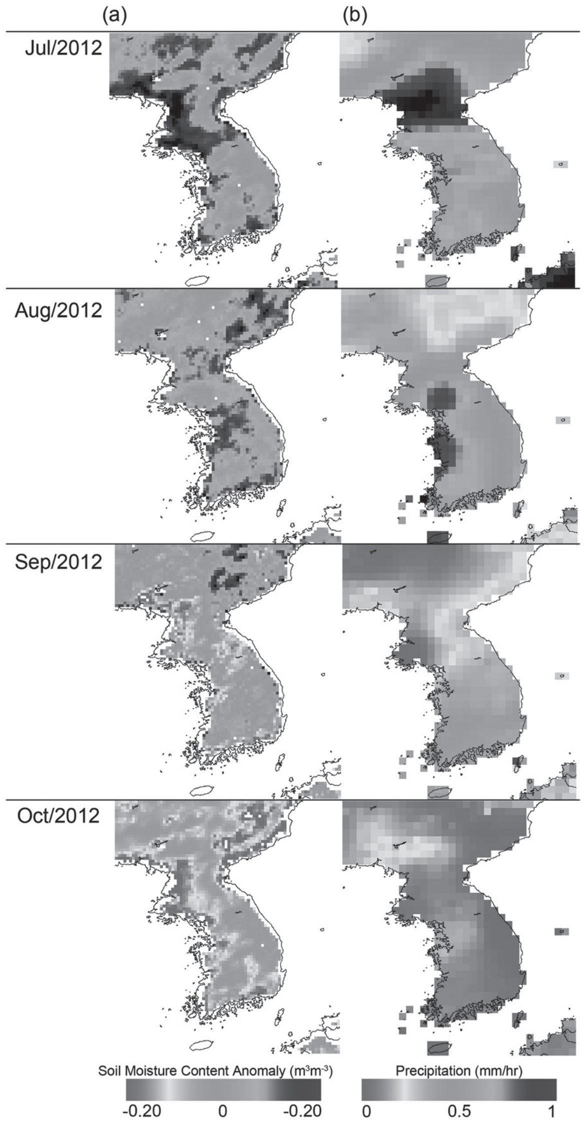

Fig. 5. Comparison between the monthly distributions of (a) anomaly of the AMSR2 SMC and (b) the TRMM precipitation.

be moderately well correlated. In July and August, the anomaly of the soil moisture was generally high and in the regions with higher precipitation, the northern part in July and the western part in August, a responding increase in the soil moisture existed. The discordance of some of the area that was found in the patterns in July and August was partially due to the episodic characteristics of the rainfall events (KMA 2012; Cho and Choi 2014). In July, most of the precipitation occurred in the early to middle of the month, followed by extremely high temperatures, which would have caused high evaporation that would lead to a rapid decrease in the soil moisture. Draper et al. (2009) reported a similar pattern in the spatial distribution found between the monthly AMSR-E soil moisture data and monthly precipitation, over Australia. As the precipitation stayed low from September to October, the soil moisture was also evenly distributed with a low average. Although there were differences in the spatio-temporal scale in the analysis of the spatial distribution of the soil moisture and precipitation, it can be concluded that the soil moisture observed by the AMSR2 responded well to the precipitation on the monthly time scale.

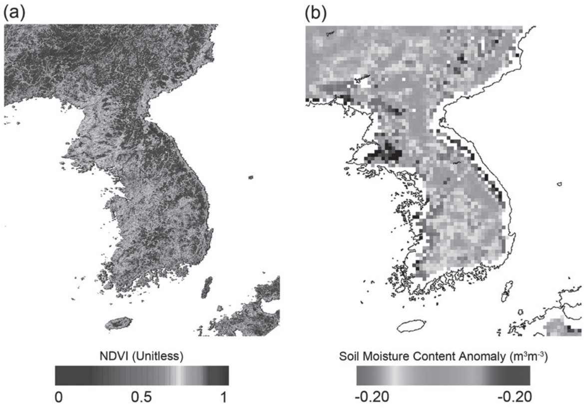

Fig. 6. Spatial distributions of (a) the NDVI and (b) anomaly of the AMSR2 soil moisture on July 31, 2012.

Figure 6 shows the spatial distributions of the Normalized Difference Vegetation Index (NDVI) and soil moisture anomaly with the mean of July and August soil moisture as reference under dry conditions. In wet conditions, the NDVI and soil moisture were rarely correlated (not shown here), since the climate conditions (e.g., precipitation) dominantly affected the SMCs (Lakshmi et al. 2004; Wang et al. 2007). The dry conditions were determined by the occurrences of rainfall; precipitation was rarely detected four days before and after 31st July. As the eastern region of Korea has a higher NDVI value than the western region, the soil moisture anomaly showed a roughly similar pattern to it. Consequently, the analysis of Figs. 5 and 6 indicated that the spatial pattern of the soil moisture had a partially reasonable agreement with the relevant meteorological and agricultural variables in northeast Asia and thus the downscaling method can be further applied to improve the spatial resolution and accuracy based on the identified relation between those variables and soil moisture as in previous studies (Kim and Hogue 2012; Choi and Hur 2012; Fang et al. 2013; Fang and Lakshmi 2014).

5. Conclusions

The AMSR2 soil moisture showed prospective results in capturing both the temporal and spatial variations of the moisture conditions in northeast Asia. Temporally, the comparison between the in situ soil moisture and the AMSR2 soil moisture displayed a reasonable response of the soil moisture to the rainfall events at each site, although there were occasionally unforeseeable AMSR2 values. Furthermore, we implemented a filtering and normalization process in order to get rid of the noise and systematic differences. This process provided a quality improvement in the satellite-based soil moisture, and the AMSR2 data eventually showed good agreement with the in situ measurement data. The error estimates from the TC analysis showed that the AMSR2 SMC product generally had larger systematic errors than the in situ and GLDAS soil moisture, which is in agreement with the TC-based error estimates of the AMSR-E in previous studies. The spatial distribution of the AMSR2 soil moisture indicated that the retrieved product succeeded in capturing the seasonal variations in the soil moisture. On a monthly scale, the spatial pattern of the AMSR2 soil moisture corresponded with that of the precipitation. Under dry conditions, the distribution of the soil moisture also matched the distribution of the NDVI.

The results of this study can be helpful for estimating the regional soil moisture distribution, taking into consideration the period of the monsoon season in northeast Asia, as well as validating and calibrating the microwave satellite soil moisture products derived by the Metop-B and the upcoming Soil Moisture Active Passive mission. For a better understanding of the current findings, further validation study at a broader area during a longer period will be conducted after the completion of the calibration of AMSR2 datasets.

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