International Journal of Applied Earth Observation and Geoinformation 45 (2016) 187–199

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

# Evaluation of AMSR2 soil moisture products over the contiguous United States using *in situ* data from the International Soil Moisture Network

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A R T I C L E   I N F O

*Article history:*
Received 12 March 2015
Received in revised form 15 October 2015
Accepted 16 October 2015
Available online 29 October 2015

*Keywords:*
AMSR2
Soil moisture
Passive microwave
Remote sensing
International Soil Moisture Network

A B S T R A C T

High quality soil moisture datasets are required for various environmental applications. The launch of the Advanced Microwave Scanning Radiometer 2 (AMSR2) on board the Global Change Observation Mission 1—Water (GCOM-W1) in May 2012 has provided global near-surface soil moisture data, with an average revisit frequency of two days. Since AMSR2 is a new passive microwave system in operation, it is very important to evaluate the quality of AMSR2 products before widespread utilization of the data for scientific research. In this paper, we provide a comprehensive evaluation of the AMSR2 soil moisture products retrieved by the Japan Aerospace Exploration Agency (JAXA) algorithm. The evaluation was performed for a three-year period (July 2012–June 2015) over the contiguous United States. The AMSR2 soil moisture products were evaluated by comparing ascending and descending overpass products to each other as well as comparing them to *in situ* soil moisture observations of 598 monitoring stations obtained from the International Soil Moisture Network (ISMN). The accuracy of AMSR2 soil moisture product was evaluated against several types of monitoring networks, and for different land cover types and ecoregions. Three performance metrics, including mean difference (MD), root mean squared difference (RMSD), and correlation coefficient ($R$), were used in our accuracy assessment. Our evaluation results revealed that AMSR2 soil moisture retrievals are generally lower than *in situ* measurements. The AMSR2 soil moisture retrievals showed the best agreement with *in situ* measurements over the Great Plains and the worst agreement over forested areas. This study offers insights into the suitability and reliability of AMSR2 soil moisture products for different ecoregions. Although AMSR2 soil moisture retrievals represent useful and effective measurements for some regions, further studies are required to improve the data accuracy.


## 1. Introduction

Soil moisture plays a key role in the interaction between the atmosphere and hydrosphere. It controls the partition of precipitation into infiltration and surface runoff, and the partition of available energy between sensible and latent heat flux (Houser, 2005). High quality soil moisture measurements are needed for various applications, including short-term weather prediction (Drusch, 2007; Van Den Hurk et al., 1997), crop yield forecast (Doraiswamy et al., 2003; Prasad et al., 2006), drought monitoring (Choi et al., 2013; Jackson, 2005; Narasimhan and Srinivasan, 2005), and climate change studies (Al Bitar et al., 2012; Koster et al., 2004). A good knowledge of the spatiotemporal variability of soil moisture would be crucial, particularly for arid and semi-arid agricultural regions where regular irrigations are often required but water resources are very limited. Soil moisture information can be acquired by either *in situ* soil moisture instruments, by land surface models, or by remote sensing technology. In the past two decades, various studies have demonstrated that soil moisture can be retrieved by a variety of sensors, including optical, thermal, passive microwave and active microwave instruments (Albergel et al., 2013). The passive microwave satellite sensors, such as Special Sensor Microwave/Imager (SSM/I), Advanced Microwave Scanning Radiometer on the Earth Observing System (AMSR-E), and Soil Moisture and Ocean Salinity (SMOS), have been quite successful in

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http://dx.doi.org/10.1016/j.jag.2015.10.011
0303-2434/

providing global soil moisture products (Jackson, 2005; Kerr et al., 2010; Njoku et al., 2003; Wigneron et al., 1998).

The AMSR-E on board the NASA Aqua satellite was launched on May 4, 2002. However, it stopped producing data due to a problem with the rotation of its antenna since October 2011 (Al-Yaari et al., 2014). The Advanced Microwave Scanning Radiometer 2 (AMSR2) on board the Global Change Observation Mission 1—Water (GCOM-W1) was launched on May 18, 2012 by the Japan Aerospace Exploration Agency (JAXA) as a successor to AMSR-E. The GCOM-W1 is the first generation of the GCOM satellite series, which aim to establish the global and long-term observations for understanding global water and energy circulation. AMSR2 measures the brightness temperatures at seven different frequencies, including 6.925/7.3 GHz, 10.65 GHz, 18.7 GHz, 23.8 GHz, 36.5 GHz, and 89.0 GHz. Basic concept of AMSR2 is almost identical to that of AMSR-E (Kachi et al., 2014). A key difference of AMSR2 in comparison with AMSR-E is that a new 7.3-GHz channel was added to AMSR2 because Radio Frequency Interference (RFI) signals were frequently found in the 6.925-GHz brightness temperatures of AMSR-E (Njoku et al., 2005). The geophysical products provided by AMSR2 include integrated water vapor, integrated cloud liquid water, precipitation, sea surface temperature, sea surface wind speed, sea ice concentration, snow depth, and soil moisture content. The AMSR2 can obtain coverage for the majority of the Earth's surface within two days, providing a swath of 1450 km. Local crossing times are around 1:30 p.m. and 1:30 a.m. respectively for ascending and descending overpasses. The commission phase was completed at the end of 2012. The Level 1 (brightness temperature) and Level 2 (geophysical products) data have been released to the public since January and May 2013, respectively. Since AMSR2 is the successor to AMSR-E with almost identical frequency channels, it is expected to sense and record soil moisture content contained in the top ~1 cm of the soil layer on average for low vegetated areas (Imaoka et al., 2010; Jackson et al., 2010; Njoku et al., 2003). Satellite soil moisture retrievals can be affected by vegetation, surface roughness, atmospheric water vapor, soil wetness and texture, physical temperatures, and other attenuating components. Previous studies demonstrated that the presence of dense vegetation cover may pose a serious problem for passive microwave sensors to detect soil moisture, particularly for those sensors with relatively short wavelength (Dorigo et al., 2010; Jackson and Schmugge, 1991; Mladenova et al., 2014; Ulaby et al., 1983). Soil moisture can be retrieved from the observed brightness temperature for both ascending and descending overpasses. Previous studies showed that the retrievals from satellite descending overpasses (1:30 a.m., nighttime) reflect surface soil moisture condition better than from ascending overpasses (1:30 p.m., daytime), because the temperature and moisture profiles tend to be more nearly uniform and in equilibrium situation during nighttime (Njoku et al., 2003; Norouzi et al., 2011).

Since AMSR2 is a new passive microwave system in operation, it is very important to evaluate its data quality before widespread utilization of the data for scientific research. JAXA has conducted calibration and validation activities with various collaborating agencies in Mongolia, Thailand, Australia, and the U.S. (Kachi et al., 2008; Kaihotsu et al., 2013; Oki et al., 2012). However, validation efforts have in general been hampered by limited availability of intensive field campaigns for collecting ground truth data. The aforementioned validation studies only focused on limited sites where multiple *in situ* soil moisture measurements were available within a satellite footprint for a relatively short time period (1–6 months). More recently, Parinussa et al. (2014) conducted a preliminary study on AMSR2 soil moisture products (from July 12 to August 2013) retrieved by the Land Parameter Retrieval Model (LPRM) algorithm, developed by the VU University Amsterdam in collaboration with the National Aeronautics and Space Administration. LPRM is based on a simple radiative transfer model, which simulates observed brightness temperature by varying three land surface variables (vegetation optical depth, topsoil dielectric constant and surface temperature) to partition microwave observation into soil and vegetation components. More information on this retrieval algorithm can be found in a range of publications (Cho et al., 2015a; Dorigo et al., 2015; Kim et al., 2015; Owe et al., 2008; Su et al., 2014, 2013). Apart from the LPRM algorithm, JAXA also developed a soil moisture retrieval algorithm (Fujii et al., 2009) for AMSR2 and has made its soil moisture products available since July 2012. Both algorithms use a simple radiative transfer model as the starting point, but they have differences in estimating physical surface temperature, surface roughness, vegetation dynamics and dielectric mixing models. Kim et al. (2015) made a detailed comparison between these two algorithms and evaluated the two soil moisture products at the global scale using field measurements from 47 monitoring stations over the period July 2012 through August 2013. It was found that absolute values of the JAXA soil moisture are generally lower than the LPRM soil moisture.

In this paper, we attempt to evaluate the AMSR2 soil moisture products (JAXA algorithm) over the contiguous U.S. by using *in situ* data of 598 monitoring stations from four different networks distributed through the freely accessible International Soil Moisture Network (Dorigo et al., 2011) for a three-year period (July 3, 2012–June 3, 2015). These stations represent a variety of conditions across the contiguous U.S. We conducted the evaluation of AMSR2 soil moisture products in terms of different climate and ecoregions so as to provide a more useful guideline for the suitability and reliability of AMSR2 soil moisture products for different types of geographic regions.

## 2. Data sets

### 2.1. AMSR2 soil moisture products

Our evaluation mainly focuses on the AMSR2 Level 3 (L3) Soil Moisture Content (SMC) data products (JAXA algorithm), which have been released since May 17, 2013 by the GCOM-W1 Data Providing Service (https://gcom-w1.jaxa.jp/, accessed September 2015). The AMSR2 L3 SMC products are provided as daily and monthly temporal average grid data with 0.1°/0.25° (10/25 km) spatial resolution in Equidistant Cylindrical Projection. The SMC products are presented as volumetric water content over global land regions where the vegetation water content equivalent is 2 kg/m$^2$ or less (JAXA, 2013b). A detailed description of the AMSR2 soil moisture retrieval algorithm is provided in (JAXA, 2013a) and the Level 3 product format specification is provided in (JAXA, 2013c). The required release accuracy for AMSR2 SMC products is $\pm 0.1\,m^3\,m^{-3}$, while the desired goal accuracy is $\pm 0.05\,m^3\,m^{-3}$. The required release accuracy is the minimum accuracy of data that can be released for use in climate change analyses, while the goal accuracy is the accuracy level that is desirable with algorithm performance and calibration accuracy improvement (Maeda et al., 2011). This study focuses on SMC daily products at the 0.1° grid for a three-year period (July 3, 2012–June 3, 2015) over the contiguous U.S., with a total of 1065 daily soil moisture images for ascending and descending overpasses, respectively. The value range is 0–0.6 $m^3\,m^{-3}$, while the dummy value −9999 indicates no data. It should be noted that there is a product upgrade on March 26, 2015 (http://gcom-w1.jaxa.jp/information_all.html, accessed September 2015), meaning that the data quality is not consistent during the study period. This issue is outside the scope of the current study. Therefore, the effects of product upgrade on the analysis results are not assessed in the study.

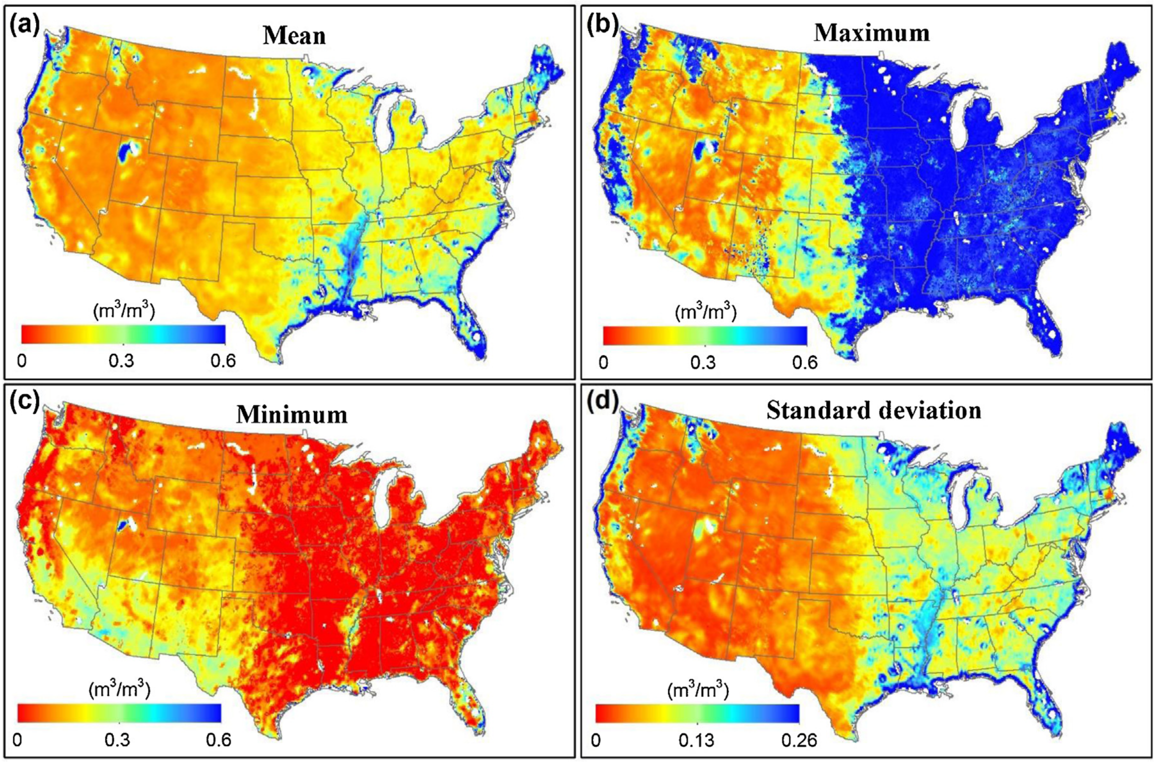


**Fig. 1.** Maps of arithmetic mean (a), maximum (b), minimum (c), and standard deviation (d) of the AMSR2 Level 3 daily soil moisture products at the 0.1° grid over the contiguous U.S. for the period July 2012 through June 2015 (descending overpasses).

Fig. 1 shows maps of arithmetic mean, maximum, minimum, and standard deviation of the AMSR2 L3 daily soil moisture products at the 0.1° grid for the period July 2012 through June 2015 (descending overpasses). It should be noted that the number of days used for calculation varies for each pixel, depending on the number of days with valid observations at each pixel from both datasets. The 0.1° grid with full coverage for the contiguous U.S. contains 79,109 pixels. Over the three-year study period (1065 days), the number of days with valid observations from both the descending and ascending overpasses ranges from 1 to 996 days, with an average of 806 (75.7%) days. It appears that the mean soil moisture values in the western U.S. are generally lower than that in the eastern U.S., with an average mean soil moisture of 0.086 $m^3 m^{-3}$ across the contiguous U.S. (Fig. 1a). Most strikingly, the maximum soil moisture values of most grid cells in the eastern U.S. are larger than 0.50 $m^3 m^{-3}$ while most grid cells in the western U.S., are lower than 0.25 $m^3 m^{-3}$, with the exception of those grid cells near the west coast. This dramatic difference can be clearly observed in Fig. 1b. Interestingly, we found that the minimum soil moisture values in the eastern U.S., are much lower than that in the western U.S. (Fig. 1c), indicating that soil moisture in the western U.S. has generally smaller value range than in the eastern U.S. The standard deviation map is presented in Fig. 1d, which clearly shows that soil moisture in the western U.S. has much lower range of variation compared to the eastern U.S.

### 2.2. International Soil Moisture Network data sets

The *in situ* soil moisture data obtained from the International Soil Moisture Network (ISMN) were used as ground truth to evaluate the AMSR2 soil moisture products in our analysis. In 2011, as part of the calibration and validation support for the SMOS satellite mission, the ISMN was initiated by the European Space Agency (ESA) to serve as a centralized data hosting facility (Dorigo et al., 2011). As of June 2015, the ISMN contains soil moisture data from 48 monitoring networks with a total of 2001 stations around the globe. More than 1100 of these stations from 12 monitoring networks are distributed over the contiguous U.S. All soil moisture data from these historical and operative networks are automatically converted into common volumetric soil moisture units with quality-control procedures to flag outliers and implausible values (Dorigo et al., 2013). These stations might provide soil moisture measurements at different depths (2–100 cm), and some stations may also provide measurements on precipitation, soil temperature, and air temperature. This study only used soil moisture observations measured at the 5-cm depth since the AMSR2 was designed and expected to sense soil moisture in the top soil skin layer. The time period of the entire ISMN database runs from 1952 until the present. All soil moisture measurements provided through the ISMN are resampled to be a 1-h temporal interval, following recommendations of World Meteorological Organizations (Dorigo et al., 2011).

Among the 1106 stations across the contiguous U.S., 722 of them have data coverage beginning July 2012, which is the starting time of the AMSR2 soil moisture products. To minimize the effect of erroneous *in situ* measurements all flagged soil moisture values (Dorigo et al., 2013) were excluded from our analysis, including those under frozen conditions; reported value exceeding soil moisture value range (<0.0 $m^3/m^3$ or >0.6 $m^3/m^3$); unnaturally positive/negative jump in soil moisture. As the hourly *in situ* observations from the ISMN are recorded on the UTC time, they were first converted to local time based on the station coordinates. After conversion, two hourly soil moisture values closest to the satellite overpass time (13:00 and 14:00 for daytime; 01:00 and 02:00 for nighttime) were averaged to represent the *in situ* soil moisture values. Accordingly, the final *in situ* dataset includes field measurements from 598 stations which have at least 6 months (180 days) overlapping (not necessarily continuous) with the three-year

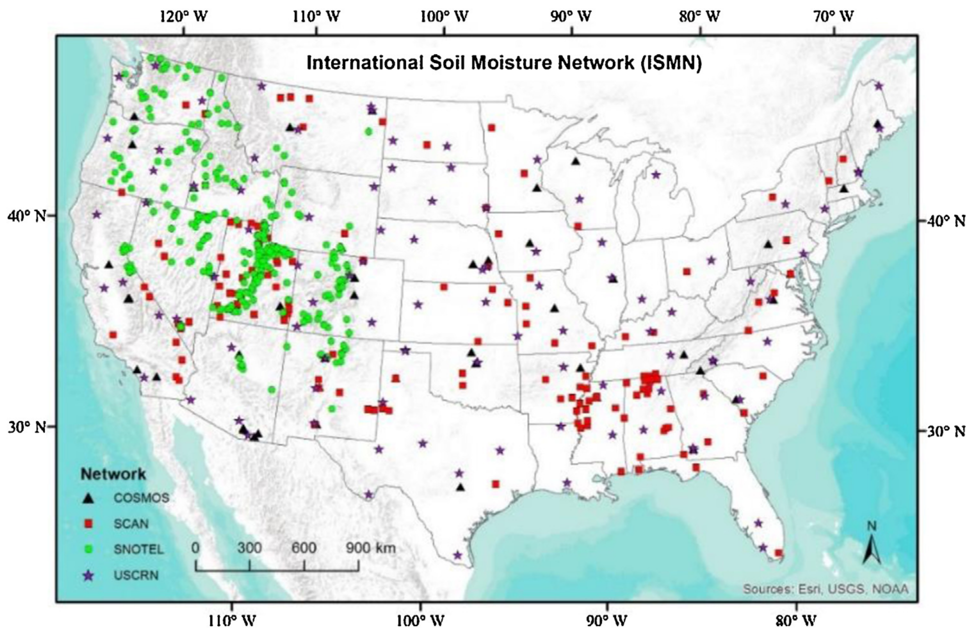


**Fig. 2.** Spatial distribution of the 598 selected monitoring stations from four operational networks.

**Table 1**
The selected number of stations of each operational network, land cover type and ecoregion across the contiguous U.S. in our study.

| Network | No. of stations |
|---|---|
| SNOTEL | 299 |
| SCAN | 150 |
| USCRN | 99 |
| COSMOS | 50 |
| Land cover type | |
| Evergreen forest | 158 |
| Shrub/scrub | 139 |
| Deciduous forest | 79 |
| Hay/pasture | 60 |
| Herbaceous | 60 |
| Cultivated crops | 58 |
| Ecoregion | |
| Northwestern Forested Mountains | 258 |
| North American Deserts | 134 |
| Eastern Temperate Forests | 104 |
| Great Plains | 69 |

AMSR2 satellite observations. These stations are from four different operational networks (Table 1), including the U.S. Department of Agriculture Soil Climate Analysis Network (SCAN; http://www.wcc.nrcs.usda.gov/scan/) (Schaefer et al., 2007), Cosmic-ray Soil Moisture Observing System (COSMOS; http://cosmos.hwr.arizona.edu/) (Zreda et al., 2008), U.S. Climate Reference Network (USCRN; http://www.ncdc.noaa.gov/crn/) (Bell et al., 2013), and Snow Telemetry (SNOTEL, http://www.wcc.nrcs.usda.gov/snow/) (Leavesley et al., 2008). The spatial distribution of the 598 selected stations is shown in Fig. 2. It should be noted that the SNOTEL stations are primarily located in western mountainous regions, while the stations from COSMOS, SCAN, and USCRN are relatively evenly distributed across the contiguous U.S.

### 2.3. National Land Cover Database (NLCD) 2011

The National Land Cover Database (NLCD) 2011 products were used to obtain the land cover type for each monitoring station used in our study across the contiguous U.S. The NLCD 2011 is the most recent national land cover product created through a cooperative project conducted by the Multi-Resolution Land Characteristics (MRLC) Consortium (http://www.mrlc.gov), which provides a 16-class land cover classification across the U.S. at a spatial resolution of 30 meters based on 2011 Landsat satellite data (Jin et al., 2013). The NLCD 2011 map overlaid with ISMN monitoring stations is shown in Fig. 3a. The 598 stations are distributed in a variety of land cover types (Table 1): 158 in evergreen forest, 139 in shrub/scrub, 79 in deciduous forest, 60 in hay/pasture, 60 in herbaceous, and 58 in cultivated crops. The remaining 44 stations are distributed in the other five minority land cover types (Fig. 3a).

### 2.4. Ecoregions of the contiguous U.S.

Ecoregions denote relatively large areas sharing a large majority of their species and ecological dynamics and having similar environmental conditions and resources. Ecological regions in the contiguous U.S. have been identified through the analysis of patterns of biotic and abiotic phenomena that affect or reflect differences in ecosystem quality and integrity (Omernik, 1987). North America was divided into 15 ecological regions at Level I, and 50 regions at Level II. The U.S. ecoregions data were downloaded from the U.S. Environmental Protection Agency (EPA) Western Ecology Division website (http://www.epa.gov/wed/pages/ecoregions.htm, accessed September 2015). The Level I ecoregion map overlaid with the ISMN monitoring stations is shown in Fig. 3b. The Northwestern Forested Mountains region contains 258 stations (43.1%), the largest number among all ecoregions. The SNOTEL network stations are primarily located in the Northwestern Forested Mountains ecoregion. The other three ecoregions with more than 50 stations include North American Deserts (134), Eastern Temperate Forests (104), and Great Plains (69), with a total of 286 stations (51.3%) (Table 1). The remaining 33 (5.6%) stations are distributed in the other six minority ecoregions (Fig. 3b).

## 3. Evaluation methods

Previous studies have adopted different approaches for filtering/scaling satellite-based soil moisture data for the comparison with *in situ* observations (Brocca et al., 2011, 2013a; Crow et al., 2012; Draper et al., 2009). In this study, the AMSR2 soil

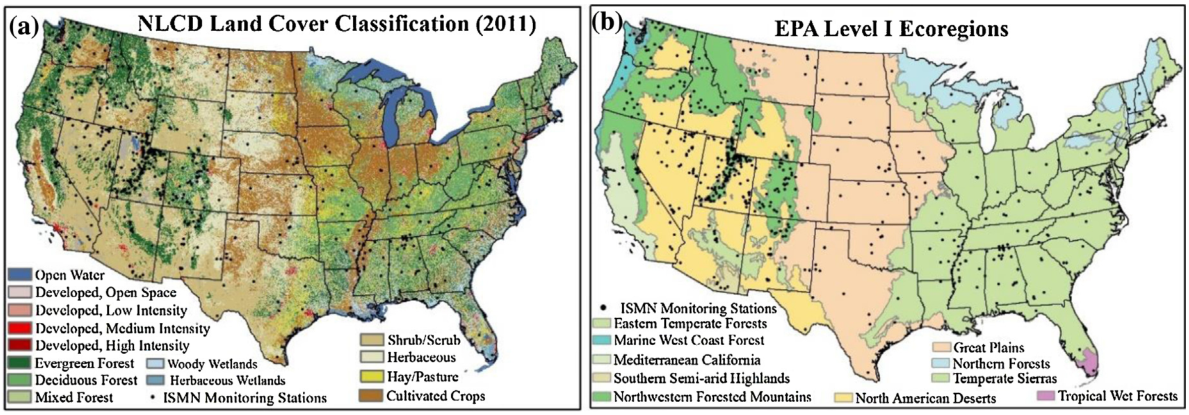


**Fig. 3.** The NLCD 2011 land cover map (a) and the Level I ecoregions map (b) of the contiguous U.S.

moisture products were evaluated by comparing the ascending and descending overpass products to each other as well as comparing them to the *in situ* soil moisture observations from ground stations of the monitoring networks, which were treated as ground truth. For comparison between ascending and descending overpass products, all grid cells (79,109) over the contiguous U.S. were examined to evaluate diurnal variation of AMSR2 soil moisture retrievals. On the contrary, when comparing the AMSR2 soil moisture products against *in situ* measurements, only those gird cells in which monitoring stations are located were used for evaluation. When more than one station is located within the same grid cell, their field measurements were averaged to represent the ground truth in that grid cell. The AMSR2 soil moisture products were compared against the ISMN soil moisture measurements for both original data and anomaly data. The anomaly data was derived in two steps (Dorigo et al., 2015; Kim et al., 2015). The first step was to calculate the seasonal cycle by taking a 31-day moving average over the period 18 July 2012 through 19 May 2015, while the data actually used is from 3 July 2012 through 3 June 2015. The second step was to calculate the anomaly data by removing seasonal cycle from the original data. The accuracy of AMSR2 soil moisture products is characterized in terms of three statistical indicators: mean difference (MD), root mean squared difference (RMSD), and correlation coefficient ($R$). The mean difference is given by:

$$\mathrm{MD} = \frac{\sum_{t=1}^{N} \left(\theta_{\mathrm{s}}(t) - \theta_{\mathrm{m}}(t)\right)}{N} \tag{1}$$

where $\theta_{\mathrm{s}}$ is the satellite soil moisture retrieval ($\mathrm{m}^3\,\mathrm{m}^{-3}$), and $\theta_{\mathrm{m}}$ is the *in situ* soil moisture measurement ($\mathrm{m}^3\,\mathrm{m}^{-3}$). $t$ represents specific daily time step and $N$ is the total number of time steps in the analysis. It should be noted that $N$ varies for each grid cell. Only dates which have valid data from both datasets were used for calculation. When calculating the mean difference of soil moisture between ascending and descending overpasses, $\theta_{\mathrm{s}}$ represents descending (nighttime) retrieval and $\theta_{\mathrm{m}}$ is the ascending (daytime) retrieval. The above definitions are also valid for the following equations. The root mean squared difference (RMSD) is calculated as:

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{t=1}^{N} \left(\theta_{\mathrm{s}}(t) - \theta_{\mathrm{m}}(t)\right)^2}{N}} \tag{2}$$

The correlation coefficient $R$ for the evaluation of the AMSR2 soil moisture against *in situ* soil moisture is calculated by:

$$R = \frac{\sum_{t=1}^{N} \left(\theta_{\mathrm{s}}(t) - \mu_{\mathrm{s}}\right)\left(\theta_{\mathrm{m}}(t) - \mu_{\mathrm{m}}\right)}{(N-1)\,\sigma_{\mathrm{s}}\sigma_{\mathrm{m}}} \tag{3}$$

where $\mu_{\mathrm{s}}$ is the average AMSR2 soil moisture over the entire evaluation period in a footprint ($\mathrm{m}^3\mathrm{m}^{-3}$), and $\mu_{\mathrm{m}}$ is the average of *in situ* soil moisture measurements ($\mathrm{m}^3\,\mathrm{m}^{-3}$). $\sigma_{\mathrm{s}}$ and $\sigma_{\mathrm{m}}$ are respectively the standard deviation of satellite and *in situ* soil moisture ($\mathrm{m}^3\,\mathrm{m}^{-3}$) and $N$ is the total number of time steps in the analysis.

The mean difference MD represents the bias, namely the systematic difference between AMSR2 soil moisture retrievals and *in situ* soil moisture measurements; the root mean squared difference RMSD represents the absolute difference/accuracy of AMSR2 soil moisture retrievals against *in situ* soil moisture measurements; and the correlation coefficient $R$ shows the temporal consistency and relative accuracy between AMSR2 soil moisture retrievals and *in situ* soil moisture measurements. We calculated these three statistical indicators at a daily timescale over the three-year period (July 2012–June 2015). In order to evaluate the AMSR2 soil moisture products (JAXA algorithm) in different geographical environments, the three accuracy indicators were computed for different land cover types and different ecoregions. To understand the agreement and consistency between AMSR2 satellite retrievals and *in situ* sensors of different ground networks, the three accuracy indicators were also computed separately for each type of *in situ* monitoring networks.

## 4. Results

The statistical accuracy indicators of soil moisture retrievals were calculated and shown in Figs. 4–7 and Tables 2–4 for different monitoring networks, different land cover types, and different ecoregions. We first examined the diurnal variation of soil moisture retrievals between AMSR2 descending (nighttime) and ascending (daytime) overpasses. We then evaluated the performance of AMSR2 soil moisture products by comparing the daily satellite-based soil moisture retrievals (descending overpass) to the ground-based *in situ* observations of 598 stations from four different operational networks distributed through the International Soil Moisture Network. The box plots in Figs. 5–7 present the median (the horizontal line inside each box), the mean (black dot), the 1st quantile $Q_1$ and 3rd quantile $Q_3$ (as indicated by the bottom and top of the box), the interquantile range IQR (the height of the box: $Q_3 - Q_1$), and the $Q_1 - 1.5 \times \mathrm{IQR}$ and $Q_3 + 1.5 \times \mathrm{IQR}$ values (whiskers).

### 4.1. Diurnal variation of AMSR2 soil moisture retrievals

For each grid cell in the contiguous U.S. over the period July 2012 through June 2015, we compared the AMSR2 soil moisture retrievals between satellite nighttime (descending at 1:30 a.m. local time) and daytime (ascending at 1:30 p.m. local time) overpasses. The mean difference (MD) indicator (Eq. (1)) is calculated by subtracting the daytime overpass soil moisture value from the

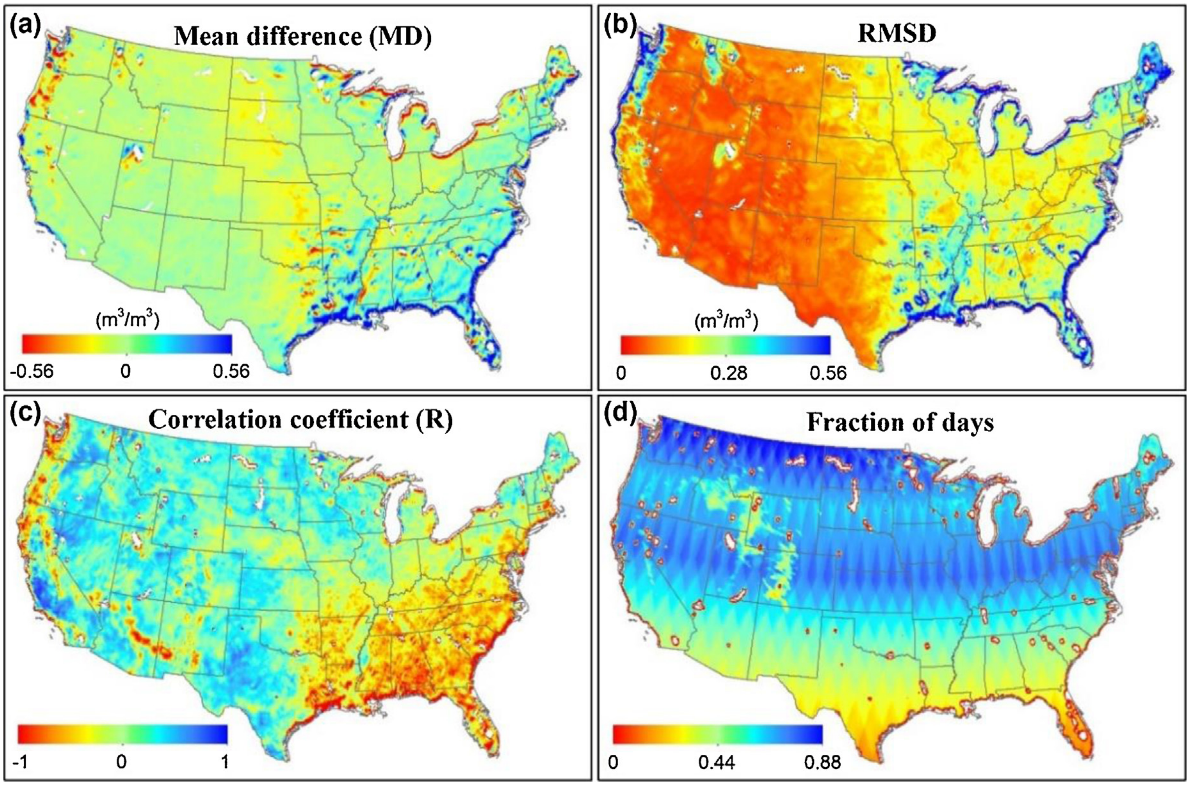


**Fig. 4.** Spatial distribution of difference between the AMSR2 nighttime and daytime retrievals for the period of 3 July 2012 through 3 June 2015. (a) Mean difference; (b) root mean squared difference (RMSD); (c) correlation coefficient ($R$); and (d) fraction of days used for calculation. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

**Table 2**
Summary statistics of differences between AMSR2 nighttime and daytime soil moisture retrievals across the contiguous U.S. (July 2012–June 2015).

| | | Mean difference | | RMSD | | Correlation ($R$) | |
|---|---|---|---|---|---|---|---|
| **Land cover type** | **Pixels** | Avg | Std | Avg | Std | Avg | Std |
| Evergreen Forest | 9,528 | -0.008 | 0.047 | 0.063 | 0.065 | 0.466 | 0.199 |
| Shrub/Scrub | 17,698 | -0.007 | 0.023 | 0.028 | 0.035 | 0.598 | 0.149 |
| Deciduous Forest | 8,898 | -0.007 | 0.032 | 0.083 | 0.039 | 0.427 | 0.154 |
| Hay/Pasture | 5,304 | -0.010 | 0.038 | 0.081 | 0.043 | 0.448 | 0.175 |
| Herbaceous | 12,312 | -0.016 | 0.022 | 0.044 | 0.030 | 0.577 | 0.131 |
| Cultivated Crops | 13,387 | -0.011 | 0.026 | 0.065 | 0.035 | 0.562 | 0.143 |
| **Ecoregion** | **Pixels** | Avg | Std | Avg | Std | Avg | Std |
| Northwestern Forested Mountains | 9,153 | -0.016 | 0.022 | 0.039 | 0.042 | 0.549 | 0.153 |
| North American Deserts | 14,435 | -0.008 | 0.009 | 0.018 | 0.011 | 0.630 | 0.110 |
| Eastern Temperate Forests | 24,440 | 0.004 | 0.054 | 0.094 | 0.054 | 0.377 | 0.175 |
| Great Plains | 23,421 | -0.015 | 0.025 | 0.051 | 0.030 | 0.592 | 0.115 |

nighttime value. A positive bias value indicates that the nighttime soil moisture retrieval is larger (wetter) than the daytime retrieval, while a negative value indicates that the nighttime soil moisture retrieval is lower (drier) than the daytime retrieval. As shown in Fig. 4a, at most grid cells, the daily soil moisture retrievals from the nighttime overpass tend to be marginally lower than those from the daytime overpass. Overall, the soil moisture retrievals from nighttime overpass are lower than those from the daytime overpass by 0.005–0.025 $m^3 m^{-3}$, with an average negative bias of $-0.0075\,m^3 m^{-3}$. Most grid cells with positive biases (see blue color in Fig. 4a)) are concentrated on coastal areas of the East Coast and Gulf of Mexico. Similarly, grid cells with high RMSD (Fig. 4b) between nighttime and daytime retrievals are predominantly located in the coastal areas of the East Coast, Gulf of Mexico, and West Coast of the United States. In general, it appears that the western U.S. has a smaller RMSD than the eastern U.S., indicating that larger diurnal variations are observed by the soil moisture retrievals in the eastern U.S. The RMSD across the contiguous U.S. ranged from 0 to 0.56 $m^3 m^{-3}$, with an average of 0.06 $m^3 m^{-3}$. The correlation coefficient map (Fig. 4c) shows a similar pattern to the RMSD map (Fig. 4b). However, negative correlations between nighttime and daytime retrievals are found in most states of the eastern U.S. (see yellow and red color in Fig. 4c), indicating poor temporal consistency between nighttime and daytime retrievals in these regions. The fraction of days with valid observations from both nighttime and daytime overpass over the three-year (1065 days) study period generally increases as latitudes increase (Fig. 4d). The maximum and mean fraction of days across the contiguous U.S. are 0.876 (933 days) and 0.659 (702 days), respectively.

The negative bias between nighttime (1:30 a.m.) and daytime (1:30 p.m.) retrievals contradicts the supposition that soil moisture should be at its driest in the afternoon. Previous AMSR-E valida-

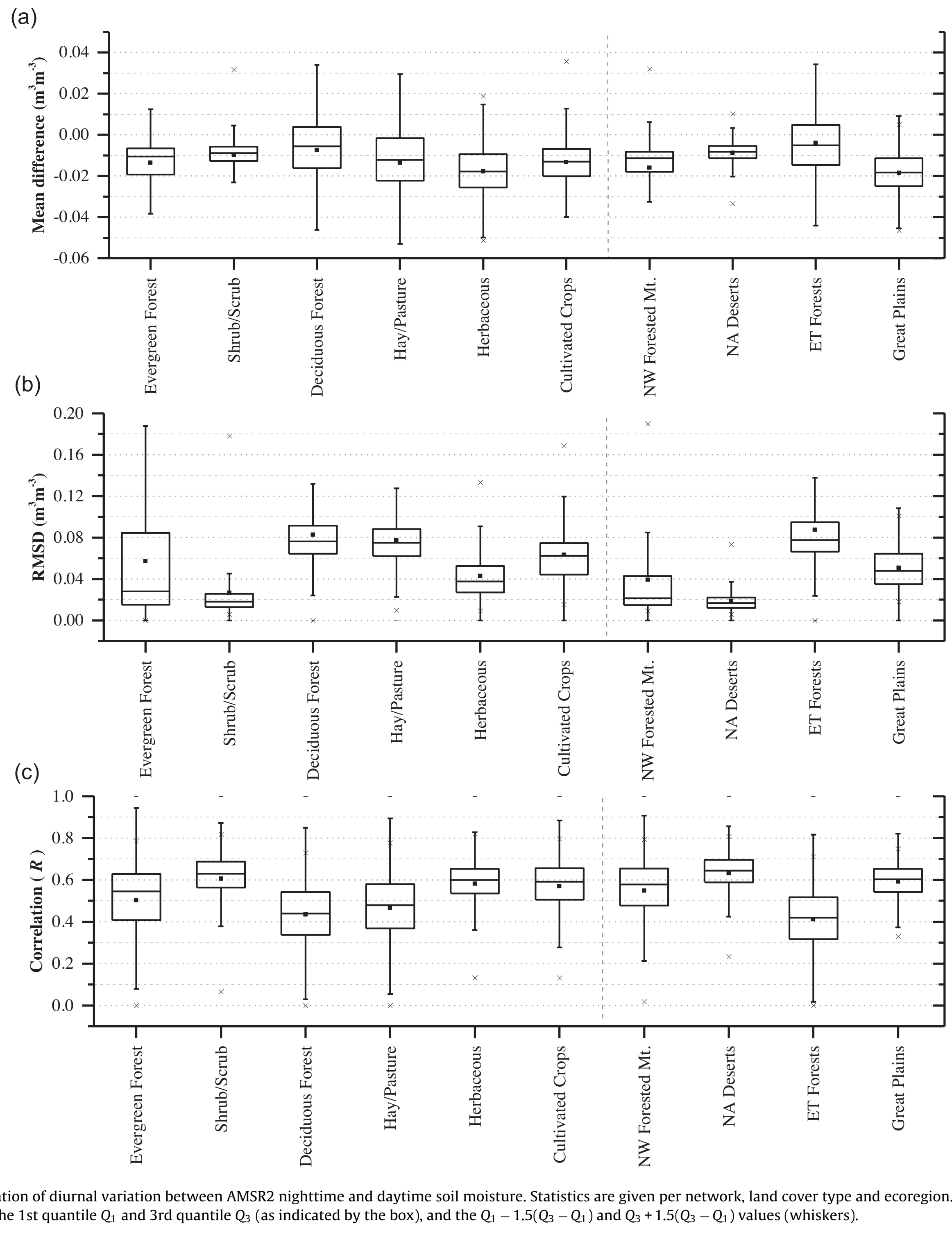


**Fig. 5.** Evaluation of diurnal variation between AMSR2 nighttime and daytime soil moisture. Statistics are given per network, land cover type and ecoregion. Presented are the median, the 1st quantile $Q_1$ and 3rd quantile $Q_3$ (as indicated by the box), and the $Q_1 - 1.5(Q_3 - Q_1)$ and $Q_3 + 1.5(Q_3 - Q_1)$ values (whiskers).

tion studies showed that the early morning (1:30 a.m.) observation occurs when the soil temperature profile tends to be more nearly uniform within the sensed soil layer and the afternoon (1:30 p.m.) observation occurs when the temperature difference between the skin and deeper layers is large (Jackson et al., 2012; Norouzi et al., 2011). As shown in Fig. 4c, the nighttime and daytime soil moisture retrievals at most grid cells have a strong correlation, with a typical correlation coefficient $R$ greater than 0.5 and the diurnal variations are small, with a typical RMSD less than 0.05 $m^3\,m^{-3}$ (Table 2). These results are consistent with previous AMSR2 validation campaign conducted in Mongolia (Kaihotsu et al., 2013) that found no significant differences between AMSR2 L3 soil moisture from daytime and nighttime overpasses. However, quantitative analysis of diurnal variations between daytime and nighttime soil moisture retrievals were not provided in their report.

In terms of land cover type, the least diurnal variations were observed over shrub/scrub with the smallest average RMSD (0.028 $m^3\,m^{-3}$). It is also interesting to see that the standard deviations of average mean difference (0.023 $m^3\,m^{-3}$) and RMSD (0.035 $m^3\,m^{-3}$) over shrub/scrub are very low, which can be evidenced from the small interquartile ranges of box plots shown in Fig. 5a, b. As shown in Fig. 3a, the shrub/scrub land cover type is

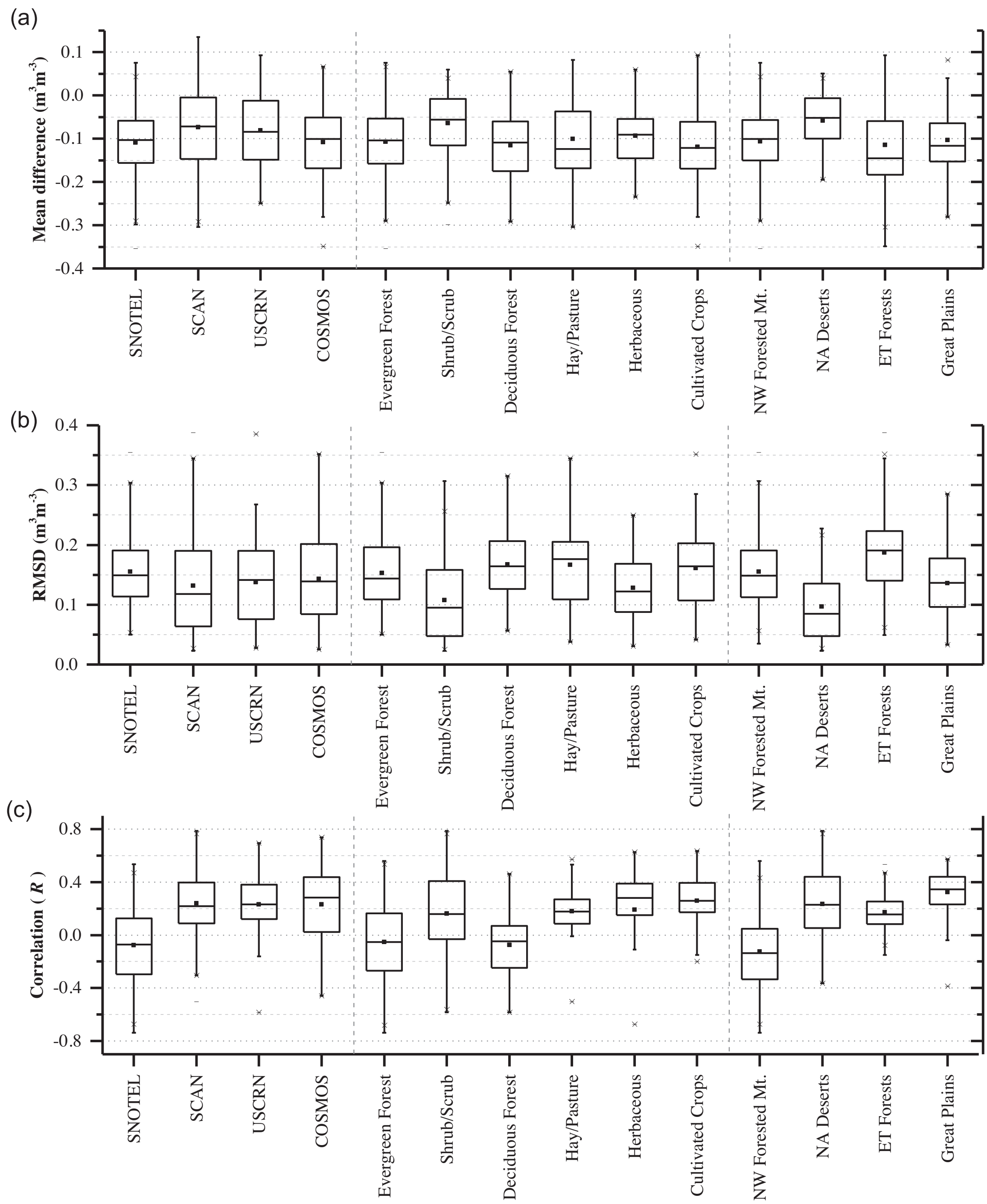


**Fig. 6.** Evaluation of AMSR2 soil moisture retrievals against *in situ* observations (original data). Statistics are given per network, land cover type and ecoregion. Presented are the median, the 1st quantile $Q_1$ and 3rd quantile $Q_3$ (as indicated by the box), and the $Q_1 - 1.5(Q_3 - Q_1)$ and $Q_3 + 1.5(Q_3 - Q_1)$ values (whiskers).

primarily distributed in deserts and semi-arid regions of the western U.S. In desert regions, the range and variation (see Fig. 1) of soil moisture values are relatively small and this fact partly explains the low values of bias and RMSD computed. This finding is consistent with results obtained in previous studies (Al-Yaari et al., 2014; Kim et al., 2015). The herbaceous land cover type has the highest average mean difference ($-0.016\,m^3\,m^{-3}$) as well as the second highest average correlation (0.577), which indicates that the nighttime and daytime retrievals over herbaceous probably have systematic diurnal variation. The summary statistics in Table 2 reveals that the AMSR2 soil moisture retrievals from nighttime and daytime overpasses have good consistency over different land cover types, with typical correlations of greater than 0.50 and typical RMSD less than $0.05\,m^3\,m^{-3}$. It should be noted that the land cover types with good consistency between nighttime and daytime retrievals do not necessarily have good consistency between AMSR2 and ISMN, which will be detailed in Section 4.2.

Regarding the soil moisture retrievals over different ecoregions, Fig. 5b and Table 2 show that North American Deserts has the smallest average RMSD ($0.018\,m^3\,m^{-3}$) and Eastern Temperate Forest has the largest average mean RMSD ($0.094\,m^3\,m^{-3}$), which implies that the smallest and largest diurnal variations are seen

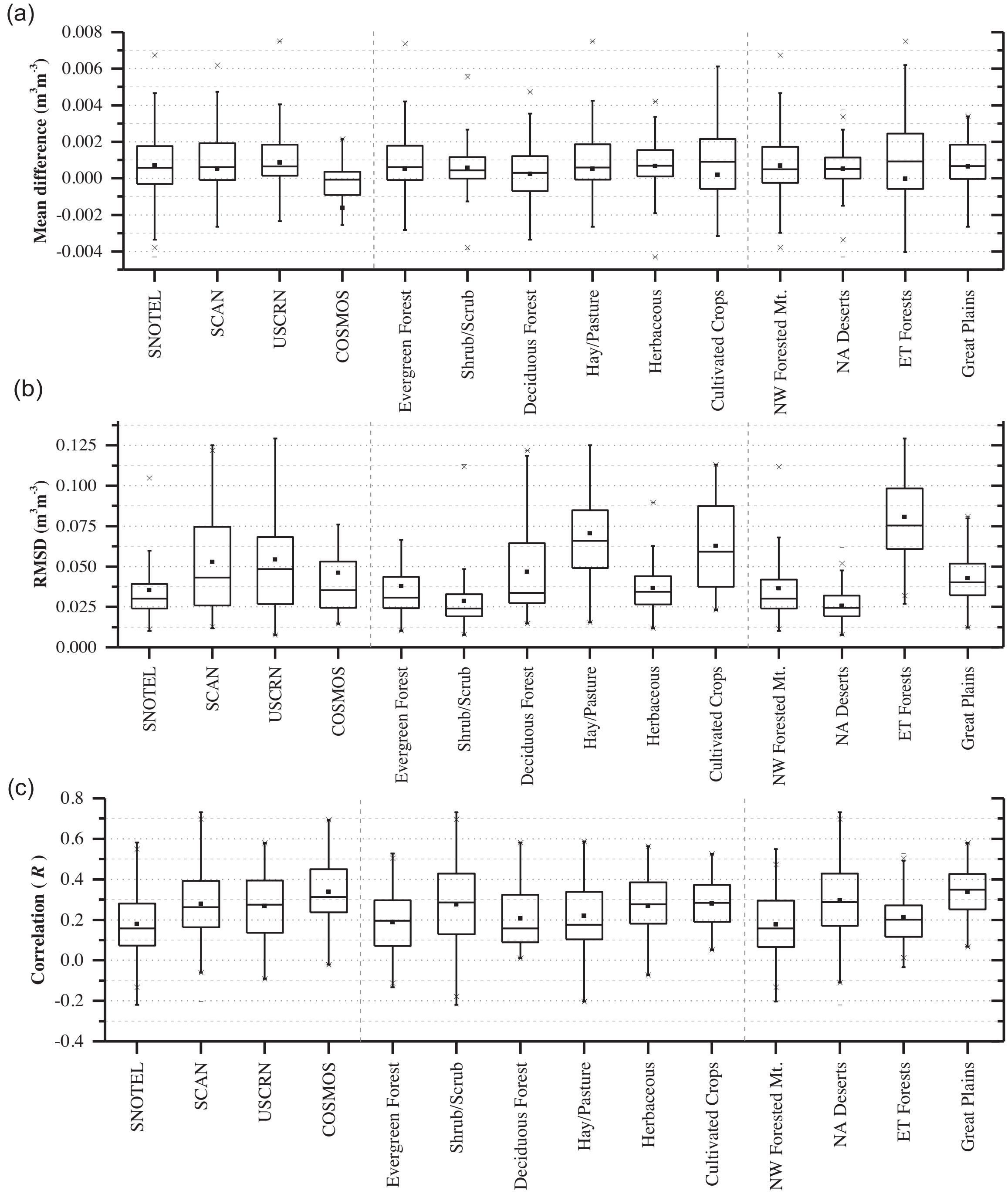


**Fig. 7.** Evaluation of AMSR2 soil moisture retrievals against *in situ* observations (anomaly data). Statistics are given per network, land cover type and ecoregion. Presented are the median, the 1st quantile $Q_1$ and 3rd quantile $Q_3$ (as indicated by the box), and the $Q_1 - 1.5(Q_3 - Q_1)$ and $Q_3 + 1.5(Q_3 - Q_1)$ values (whiskers).

in North American Deserts and Eastern Temperate Forest, respectively. This confirms the findings from previous studies showing that microwave soil moisture in desert regions exhibits much smaller diurnal amplitude than in densely vegetated areas (Norouzi et al., 2012, 2011; Prigent et al., 1999). In addition to the largest diurnal variation among all ecoregions, the Eastern Temperate Forests has the lowest mean correlation (0.377) with the largest standard deviation (0.175). On the contrary, the Great Plains has the highest correlation (0.592) with small standard deviation (0.115). These results indicate that the nighttime and daytime AMSR2 soil moisture retrievals exhibit the best temporal consistency over Great Plains and the worst temporal consistency over Eastern Temperate Forests. The worst temporal consistency observed over the Eastern Temperate Forests might be attributed to the assumption of the JAXA algorithm, which assumes that soil temperature ($T_s$) and vegetation canopy temperature ($T_c$) are fixed at a constant value of 293 K throughout the year globally (JAXA, 2013a; Kim et al., 2015). This assumption is likely invalid over the Eastern Temperate Forests with dense vegetation cover.

### 4.2. Comparison of AMSR2 and *in situ* soil moisture

The result comparisons between satellite-based retrievals and *in situ* observations at daytime and nighttime are similar. Since the nighttime (descending) microwave satellite data was generally expected to obtain more accurate soil moisture estimates than the

**Table 3**
Summary statistics of difference between AMSR2 soil moisture retrievals and *in situ* observations (original data).

| | | Mean difference | | RMSD | | *R* | |
|---|---|---|---|---|---|---|---|
| **Network** | **Stations** | Avg | Std | Avg | Std | Avg | Std |
| SNOTEL | 299 | -0.109 | 0.070 | 0.155 | 0.055 | -0.077 | 0.271 |
| SCAN | 150 | -0.073 | 0.103 | 0.132 | 0.077 | 0.241 | 0.212 |
| USCRN | 99 | -0.080 | 0.093 | 0.138 | 0.070 | 0.231 | 0.222 |
| COSMOS | 50 | -0.108 | 0.086 | 0.143 | 0.077 | 0.230 | 0.307 |
| **Land cover type** | **Stations** | Avg | Std | Avg | Std | Avg | Std |
| Evergreen Forest | 158 | -0.107 | 0.075 | 0.153 | 0.059 | -0.053 | 0.287 |
| Shrub/Scrub | 139 | -0.065 | 0.069 | 0.108 | 0.062 | 0.162 | 0.314 |
| Deciduous Forest | 79 | -0.116 | 0.073 | 0.167 | 0.052 | -0.075 | 0.222 |
| Hay/Pasture | 60 | -0.101 | 0.106 | 0.167 | 0.068 | 0.179 | 0.189 |
| Herbaceous | 60 | -0.093 | 0.070 | 0.128 | 0.055 | 0.190 | 0.323 |
| Cultivated Crops | 58 | -0.119 | 0.085 | 0.161 | 0.064 | 0.260 | 0.173 |
| **Ecoregion** | **Stations** | Avg | Std | Avg | Std | Avg | Std |
| Northwestern Forested Mountains | 258 | -0.107 | 0.070 | 0.155 | 0.056 | -0.126 | 0.260 |
| North American Deserts | 134 | -0.058 | 0.062 | 0.097 | 0.054 | 0.234 | 0.260 |
| Eastern Temperate Forests | 104 | -0.115 | 0.118 | 0.187 | 0.064 | 0.171 | 0.132 |
| Great Plains | 69 | -0.103 | 0.079 | 0.136 | 0.062 | 0.324 | 0.157 |

**Table 4**
Summary statistics of difference between AMSR2 soil moisture retrievals and *in situ* observations (anomaly data).

| | | Mean difference | | RMSD | | *R* | |
|---|---|---|---|---|---|---|---|
| **Network** | **Stations** | Avg | Std | Avg | Std | Avg | Std |
| SNOTEL | 299 | 0.0007 | 0.0018 | 0.035 | 0.019 | 0.179 | 0.144 |
| SCAN | 150 | 0.0005 | 0.0030 | 0.053 | 0.031 | 0.278 | 0.159 |
| USCRN | 99 | 0.0009 | 0.0025 | 0.054 | 0.037 | 0.268 | 0.151 |
| COSMOS | 50 | -0.0016 | 0.0056 | 0.046 | 0.035 | 0.338 | 0.171 |
| **Land cover type** | **Stations** | Avg | Std | Avg | Std | Avg | Std |
| Evergreen Forest | 158 | 0.0005 | 0.0033 | 0.038 | 0.025 | 0.189 | 0.142 |
| Shrub/Scrub | 139 | 0.0006 | 0.0014 | 0.029 | 0.018 | 0.276 | 0.200 |
| Deciduous Forest | 79 | 0.0002 | 0.0017 | 0.047 | 0.027 | 0.206 | 0.136 |
| Hay/Pasture | 60 | 0.0005 | 0.0038 | 0.071 | 0.035 | 0.218 | 0.160 |
| Herbaceous | 60 | 0.0007 | 0.0015 | 0.037 | 0.015 | 0.270 | 0.145 |
| Cultivated Crops | 58 | 0.0002 | 0.0046 | 0.063 | 0.027 | 0.281 | 0.124 |
| **Ecoregion** | **Stations** | Avg | Std | Avg | Std | Avg | Std |
| Northwestern Forested Mountains | 258 | 0.0007 | 0.0019 | 0.037 | 0.021 | 0.178 | 0.141 |
| North American Deserts | 134 | 0.0005 | 0.0011 | 0.026 | 0.009 | 0.295 | 0.183 |
| Eastern Temperate Forests | 104 | 0.0000 | 0.0056 | 0.081 | 0.028 | 0.212 | 0.124 |
| Great Plains | 69 | 0.0006 | 0.0017 | 0.043 | 0.015 | 0.339 | 0.124 |

daytime (ascending) overpass (Cho et al., 2015b; Draper et al., 2009; Jackson et al., 2010; Owe et al., 2001), the following discussions will focus on the descending overpass.

### 4.2.1. *Original data comparison*

As shown in Fig. 6a, the tops of the boxes are all under 0 $m^3 m^{-3}$, regardless of monitoring network, land cover type, or ecoregion. This reveals that the AMSR2 soil moisture retrievals have a negative bias, as compared to *in situ* observations, which is evidenced by all the negative average mean differences in Table 3. The negative bias across networks ranges from $-0.073\,m^3 m^{-3}$ to $-0.109\,m^3 m^{-3}$. Additionally, it appears that SCAN and USCRN networks have smaller negative biases than SNOTEL and COSMOS (Table 3). The level of negative bias ($-0.073$ to $-0.109\,m^3 m^{-3}$) is in line with the findings in Kim et al. (2015) who also found a negative bias ($-0.09\,m^3 m^{-3}$) at the global scale between JAXA product and field measurements from 47COSMOS stations. This underestimated pattern of the AMSR2 soil moisture products is similar to that of the AMSR-E soil moisture products, which were found in previous AMSR-E validation studies (Choi and Hur, 2012; Jackson et al., 2010; Wagner et al., 2007). In terms of RMSD, there are no substantial differences between networks, ranging from $0.132\,m^3 m^{-3}$ to $0.155\,m^3 m^{-3}$ (Table 3). Cho et al. (2015b) evaluated the AMSR2 soil moisture products (JAXA algorithm) using *in situ* measurements from nine stations on the Korean peninsula during the period from July to October 2012 and found a similar level of RMSD ($0.15\,m^3 m^{-3}$) to our study. Surprisingly, the AMSR2 and *in situ* soil moisture show very weak or even negative correspondence at stations from SNOTEL network, with a nearly zero average correlation coefficient ($R = -0.077$), while fairly good correspondences ($R > 0.23$) were found in the other three networks (Table 3). As noted earlier, the SNOTEL stations are primarily located in the western forested areas (Fig. 2), which are not in a favorable condition for microwave satellite soil moisture retrievals. Kim et al. (2015) also found strong negative correlations in the seasonal cycle at stations located in forested areas where the mean enhanced vegetation index (EVI) and vegetation optical depth (VOD) are larger than the average value of all stations used in their study. The level of positive correlation coefficients (0.23–0.24) computed in our study is a bit lower than the reported results in previous AMSR2 evaluation studies (*i.e.*, $R = 0.31$ in Cho et al. (2015b); $R = 0.38$ in Kim et al. (2015)).

From Fig. 6b and Table 3, it is evident that AMSR2 soil moisture retrievals have the least absolute difference against *in situ* measurements in the Shrub/Scrub land cover (RMSD = 0.108 $m^3 m^{-3}$), which happens to be the primary land cover in the ecoregion of North American Deserts (Fig. 3). Coincidentally, lowest RMSD (0.097 $m^3 m^{-3}$) were found in North American Deserts. The low range and variation of soil moisture in desert regions partly contribute to this low RMSD. AMSR2 has the best performance over Great Plains among all four ecoregions, with the highest average correlation coefficient of 0.324 and a relatively small average RMSD of 0.136 $m^3 m^{-3}$, which barely meets the required release accuracy (0.1 $m^3 m^{-3}$) of AMSR2 soil moisture product. The Eastern Temperate Forests has the largest average RMSD (0.187 $m^3 m^{-3}$), indicating that the AMSR2 soil moisture retrievals and *in situ* soil moisture observations have the largest absolute difference over this ecoregion. Furthermore, the land cover types of Evergreen Forest and Deciduous Forest as well as the ecoregion of Northwestern Forested Mountains all exhibit negative correlation coefficients (Table 3). These performances are within our expectations. As mentioned earlier, we anticipate that AMSR2 soil moisture retrievals are of good quality in regions of sparse to moderate vegetation cover (*e.g.,* grassland, agricultural areas), and are of poor quality in regions of densely vegetated areas (*e.g.,* tropical forest).

#### *4.2.2. Anomaly data comparison*

Compared to the box plots (Fig. 6) of statistical indicators computed from the original data, the box plots (Fig. 7) computed from the anomaly data exhibit much larger variations in box height between networks, land cover types, and ecoregions. Contrary to the negative biases (Table 3) computed from the original data, Fig. 7a and Table 4 clearly show positive biases for the anomaly data, regardless of network, land cover, or ecoregion. The only exception is that the COSMOS has a negative bias of −0.0016 $m^3 m^{-3}$. Most strikingly, the majority of RMSD (Table 4) computed from the anomaly data are less than 0.05 $m^3 m^{-3}$, which meet the desired goal accuracy of the AMSR2 soil moisture products. The low value range of anomaly data with the seasonal cycle removed partly contributes to the low RMSD.

Table 4 shows that the mean correlation coefficients computed from the anomaly data are consistently higher than the mean correlation coefficients computed from the original data, regardless of monitoring networks, land cover types, or ecoregions. In addition, all negative mean correlation coefficients (Table 3) become positive mean correlation coefficients (Table 4). For example, for grid cells located in the ecoregion of Northwestern Forested Mountains, the mean correlation coefficient change from −0.126 (computed from original data) to 0.178 (computed from anomaly data). The lowest mean and standard deviation of RMSD are found in North American Deserts for both the original and anomaly data. This results could be related to the low range of variations in soil moisture in this region. The exception is found in the ecoregion of Eastern Temperate Forests, with a highest mean RMSD of 0.081 $m^3 m^{-3}$. The mean RMSD computed from anomaly data are also less than 0.05 $m^3 m^{-3}$ in Northwestern Forested Mountains and Great Plains, which meet the desired goal accuracy of the AMSR2 soil moisture products.

In terms of correlation coefficients, Figs. 6 and 7c show very similar patterns. However, all correlation coefficients computed from the anomaly data are consistently higher than those computed from the original data. It is also worthwhile to note that all correlation coefficients have become positive, ranging from 0.178 to 0.339. The AMSR2 soil moisture retrievals show the best agreement with *in situ* measurements over the Great Plains ($R$ = 0.339) and the worst agreement over the Northwestern Forested Mountains (0.178). The highest average correlation coefficient provides an indication that the Great Plains achieves the best temporal agreement between the satellite and *in situ* soil moisture anomaly datasets.

## 5. Discussion

In our analysis, we used the *in situ* soil moisture observations at monitoring stations as ground truth to evaluate AMSR2 soil moisture retrievals. A monitoring station provides soil moisture measurements at a point location, while the AMSR2 sensor measures the averaged soil moisture within the satellite footprint/pixel. Due to the coarse resolution (10 km) of AMSR2 and the spatial heterogeneity of soil moisture, the point-based *in situ* measurement may not represent the spatially averaged soil moisture field within a 10 km satellite footprint. In addition, the *in situ* soil moisture measurements used in our evaluation are from the station sensors deployed at a depth of 5 cm below the soil surface. The AMSR2 can only sense the soil moisture signal from the top ∼1 cm of soil layer, and soil moisture content deeper than ∼1 cm from the ground surface may not always be reliably represented by AMSR2 retrievals. As part of the AMSR2 calibration and validation activities, Kaihotsu et al. (2013) found that AMSR2 retrievals slightly underestimated the soil moisture contents, when compared with *in situ* measurements at a depth of 3 cm on the Mongolian Plateau. Due to the disparity in spatial cover and vertical depth of moisture measurements, we cannot expect that AMSR2 retrievals exactly match *in situ* observations at a monitoring station, even in an ideal land cover condition. A more robust soil moisture validation of AMSR2 requires high-density *in situ* monitoring stations deployed within a satellite footprint, and *in situ* soil moisture measurement at shallower depth than current deployments. Nevertheless, the limited spatial representativeness of the point-scale *in situ* sensors (in terms of point density and deployed depth) when comparing it with larger footprint-scale satellite data might still artificially inflate the error estimate above the mission accuracy goals. Besides the traditional statistical accuracy indicators (bias, correlation, and RMSD), the so-called triple collocation method for estimating the random errors of three collocated soil moisture datasets have been widely used in satellite validation studies (Dorigo et al., 2010; Gruber et al., 2013; Miralles et al., 2010).

The average mean difference between the satellite-based AMSR2 soil moisture estimates and the ground-based soil moisture measurements range from −0.058 $m^3 m^{-3}$ to −0.119 $m^3 m^{-3}$. The consistent negative values of mean difference indicate that AMSR2 soil moisture products have a dry bias when compared to the *in situ* measurements, which is in line with the findings in Kim et al. (2015) that the JAXA soil moisture are generally lower than an alternate soil moisture (*i.e.,* the LPRM product) and *in situ* observations. The dry bias may be explained for several reasons. First, it might be attributed to the limited parameterizations (JAXA, 2013a; Kim et al., 2015) and uncertainties resulting from a number of complex factors that affect the radiative transfer model (Mo et al., 1982). Second, there is a disparity in vertical depth between the remotely sensed AMSR2 data and the *in situ* data. The soil moisture content of the thin layer (∼1 cm) observed by AMSR2 will differ from the deeper layer (5 cm) measured by the *in situ* monitoring stations. The volumetric water content in the shallower remotely sense layer (∼1 cm) tends to respond more rapidly to atmospheric forcing than the deeper soil layer (5 cm) observed by *in situ* soil sensors. There might also be biases due to retrieval algorithm or brightness temperature observations in AMSR2.

It is generally acknowledged that microwave soil moisture retrievals are of good quality in regions with sparse to moderate vegetation cover and of poor quality over tropical forest where the microwaves do not penetrate the dense canopy (Brocca et al., 2013b). Our analysis results (Tables 3 and 4) show in general poor performance of the soil moisture retrievals over forested regions (*e.g.,* Eastern Temperate Forests; Northwestern Forested Mountains). The worst temporal consistencies (*e.g.,* negative correlation and large RMSD in Fig. 4) between nighttime and daytime soil moisture products were found over large lakes and coastline due to water surface effects. These findings were consistent with previous studies which have shown that the quality of soil moisture retrieval decreases with increasing vegetation intensity (*e.g.*, Brocca et al., 2013b; Dorigo et al., 2010, 2015; Su et al., 2014) and spatial heterogeneity (*e.g.*, Al Bitar et al., 2012; Loew, 2008). Forest, urban, and open water surfaces may lead to considerable biased soil moisture retrievals (Loew, 2008). Small portions of open water might significantly contaminate the soil moisture retrievals, which could result in soil moisture retrievals that are worse than the desired retrieval performance. Therefore, the findings for the coastal areas and big lakes should be carefully considered. Based on our findings, we suggest that soil moisture grid cells within five-grid-cell distance (~50 km) to the coastlines should be masked out due to the contamination issue (see Figs. 1 and 4). Information about the surface heterogeneity within the satellite footprint could help to improve the soil moisture retrievals at the regional scale.

It should be noted that the scaling techniques (Brocca et al., 2013a) commonly used in the comparison between satellite and *in situ* soil moisture time series were not employed in this study. The evaluation of the anomaly data (18 July 2012–19 May 2015) between satellite and *in situ* measurements revealed that the mean difference between two anomaly datasets at most monitoring stations ranged from −0.001 to 0.002 $m^3 m^{-3}$ (see Fig. 7 and Table 4). In addition, the majority of RMSD computed from the anomaly data are less than 0.05 $m^3 m^{-3}$, which meet the desired goal accuracy of the AMSR2 soil moisture products. The low range of mean difference and RMSD indicate that the anomaly datasets of satellite and *in situ* measurements are probably in a similar scale/magnitude. We did test the scaling techniques (linear regression and min/max correction) in our experimental study, however, we did not find significant improvements on the statistical accuracy indicators after applying the scaling techniques on the anomaly datasets. This is the reason why we did not apply the scaling techniques in this study.

## 6. Conclusions

This paper made a comprehensive evaluation of the AMSR2 Level 3 soil moisture products (JAXA algorithm) over the contiguous U.S using *in situ* data of 598 stations from four monitoring networks distributed through the International Soil Moisture Network (ISMN) as ground truths. Our analysis reveals that the AMSR2 L3 soil moisture retrievals have a dry bias around 0.1 $m^3 m^{-3}$, when compared to *in situ* observations at a depth of 5 cm. If the *in situ* observations are treated as ground truths, the absolute accuracy of AMSR2 soil moisture retrievals is 0.13–0.15 $m^3 m^{-3}$ (RMSD), which barely meets the mission required data release accuracy (0.1 $m^3 m^{-3}$) and much worse than the desired goal accuracy (0.05 $m^3 m^{-3}$).

Our analysis suggested that the performance of the AMSR2 soil moisture retrievals varies depending upon land cover types and ecoregions. The accuracy of AMSR2 soil moisture measurements is high over ecoregion of Great Plains with an average RMSD of 0.136 $m^3 m^{-3}$ and an average correlation coefficient of 0.324. The satellite retrievals do not match with *in situ* measurements well in the ecoregion of Eastern Temperate Forests, with a typical RMSD larger than 0.187 $m^3 m^{-3}$. This result is in agreement with our expectation that passive microwave soil moisture retrievals are generally of good quality over low vegetation covered areas. Our analysis showed that the diurnal variations in soil moisture detected by satellite descending and ascending overpasses are typically less than 0.05 $m^3 m^{-3}$, and that the daytime soil moisture variations are consistent and correlated with those of the nighttime soil moisture, indicated by a correlation coefficient $R$ greater than 0.5. In conclusion, the accuracy and reliability of the satellite-based AMSR2 soil moisture estimates varies depending upon land cover and ecoregions. Large variations were observed between monitoring networks and ecoregions. This issue must be addressed in future studies to improve the accuracy of AMSR2 soil moisture estimates.

## Acknowledgments

The authors would like to thank the guest editor, Dr. Wouter Dorigo, and the three anonymous reviewers. Their comments and suggestions have been very helpful for improving the quality of this paper. The authors also wish to thank JAXA and ISMN for making soil moisture data available online.

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