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Validation of SMAP surface soil moisture products with core validation sites

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ABSTRACT

The NASA Soil Moisture Active Passive (SMAP) mission has utilized a set of core validation sites as the primary methodology in assessing the soil moisture retrieval algorithm performance. Those sites provide well-calibrated in situ soil moisture measurements within SMAP product grid pixels for diverse conditions and locations. The estimation of the average soil moisture within the SMAP product grid pixels based on in situ measurements is more reliable when location specific calibration of the sensors has been performed and there is adequate replication over the spatial domain, with an up-scaling function based on analysis using independent estimates of the soil moisture distribution. SMAP fulfilled these requirements through a collaborative Cal/Val Partner program. This paper presents the results from 34 candidate core validation sites for the first eleven months of the SMAP mission. As a result of the screening of the sites prior to the availability of SMAP data, out of the 34

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candidate sites 18 sites fulfilled all the requirements at one of the resolution scales (at least). The rest of the sites are used as secondary information in algorithm evaluation. The results indicate that the SMAP radiometer-based soil moisture data product meets its expected performance of 0.04 m^3/m^3 volumetric soil moisture (unbiased root mean square error); the combined radar-radiometer product is close to its expected performance of 0.04 m^3/m^3, and the radar-based product meets its target accuracy of 0.06 m^3/m^3 (the lengths of the combined and radar-based products are truncated to about 10 weeks because of the SMAP radar failure). Upon completing the intensive Cal/Val phase of the mission the SMAP project will continue to enhance the products in the primary and extended geographic domains, in co-operation with the Cal/Val Partners, by continuing the comparisons over the existing core validation sites and inclusion of candidate sites that can address shortcomings.

1. Introduction

NASA's Soil Moisture Active Passive (SMAP) satellite mission was launched on January 31, 2015. The objective of the mission is global mapping of soil moisture and landscape freeze/thaw state. The SMAP measurements will, therefore, contribute to improved estimates of water, energy and carbon transfers between the land and atmosphere (Entekhabi et al., 2010a). The satellite employed both an L-band radar and an L-band radiometer, however, the radar instrument suffered a failure after about 11 weeks of operation. The radiometer continues to operate. The radar measurements offered higher spatial resolution (1–3 km) observations to increase the fidelity of the coarser resolution (40 km) radiometer observations. The instruments shared a rotating 6-m mesh reflector antenna on a platform in a 685-km sun-synchronous near-polar orbit, viewing the Earth's surface at a constant 40-degree incidence angle with a 1000-km swath width. The SMAP science data product suite of geophysical parameters includes estimates of surface (top 5 cm) and root-zone (down to 1-m depth) soil moisture, net ecosystem exchange of carbon (NEE), and classification of the predominant frozen/non-frozen state of the landscape. The production of soil moisture data products continues using the radiometer data alone.

There is a long history of retrieving soil moisture or soil wetness index using microwave radiometers, e.g., (Schmugge et al., 1974; Njoku and Entekhabi, 1996; Owe et al., 2008) and scatterometers, e.g., (Wagner et al., 1999). The L-band frequency regime was identified as the best choice for soil moisture retrieval using microwave radiometers about three decades ago (Schmugge et al., 1986). However, technology to support the deployment of a large enough aperture to achieve high enough spatial resolution held back spaceborne observations until the launch of ESA's SMOS (Soil Moisture and Ocean Salinity) (Kerr et al., 2010) and NASA's SMAP satellites in 2009 and 2015, respectively. Furthermore, observations at L-band have been challenged by unexpected and illegal radio frequency interference (RFI). The RFI is generated, for example, by systems that transmit outright on the protected frequency band or by systems that inadvertently leak to the protected band. In particular, it is prohibited by international agreements at the observation band of the SMAP and SMOS radiometers (1.4–1.427 GHz). The SMOS mission has suffered significantly from RFI effects in certain regions (Oliva et al., 2012). Consequently, SMAP has incorporated aggressive RFI avoidance and filtering for both the radiometer (Piepmeier et al., 2014) and radar (Spencer et al., 2013) instruments (moreover, the synthetic aperture processing is somewhat more prone to RFI effects than the real aperture pencil beam of SMAP). These approaches enabled the SMAP calibration and validation program to focus on optimizing the performance of the sensor and geophysical products immediately after the start of the data production.

Information on the reliability of remote sensing data products is essential for their utilization in scientific studies and applications. Validation approaches that provide this information vary depending on the type of product and its application. Matching the spatial scale of a remote sensing measurement with the reference measurements is a major challenge (Colliander, 2014; Jackson et al., 2014). In the case of soil moisture, several studies have investigated the reliability of the in situ measurements, e.g., (Cosh et al., 2005; Burns et al., 2014; Adams et al., 2015), spatial variability, e.g., (Choi et al., 2007; Famiglietti et al., 2008; Das and Mohanty, 2008) and the representativeness of the in situ soil moisture measurements at larger scale, e.g., (Cosh et al., 2006; Starks et al., 2006; Gruber et al., 2013;Yee et al., 2016). The focus here is on the validation of the SMAP surface soil moisture products using core validation sites (CVS), which are defined as sites that have multiple calibrated and representative soil moisture measurement locations within a SMAP pixel (Jackson et al., 2013). Comparison of the CVS and SMAP estimates is the primary basis for assessing the performance of the soil moisture retrieval algorithms, and evaluating the mission success. Previous studies have used a similar approach, e.g., (Jackson et al., 2010, 2012); however, the SMAP CVS represent a significant expansion in terms of both number of sites and diversity of land cover and soil types. SMAP also utilizes data from sparse networks (defined as those that provide a single point observation in a specific product grid cell) in its calibration and validation plan (Jackson et al., 2013, Chen et al., 2016). Sparse network measurements have been used previously (Al Bitar et al., 2012) but present challenges that compromise the evaluation of the performance in the absolute sense (Crow et al., 2012).

The challenge faced by SMAP, as well as other satellite-based soil moisture observations, e.g., (Kerr et al., 2016), is finding validation sites that meet the measurement requirements. In an effort to increase the number of CVS as well as their geographic distribution and diversity of conditions, SMAP partnered with investigators across the globe in a collaborative Cal/Val Partners program. This paper describes the SMAP mission data products, and the calibration and validation approach, the core sites and their utilization, the processing of the data for metrics computations, and the results from using the core sites in the SMAP validation.

2. SMAP data products

The SMAP mission delivers data products from its instrument measurements (Level 1), geophysical retrievals (swath based, Level 2, and daily composite, Level 3), and land surface models assimilating SMAP measurements (Level 4); see Table 1. Prior to the radar malfunction, SMAP provided three different Level 2 surface soil moisture products: 1) L2SMP is based on the SMAP radiometer measurements and provides an estimate of the soil moisture within 36-km grid cells (O'Neill et al., 2014; Chan et al., 2016), 2) L2SMA is based on the SMAP synthetic aperture radar (SAR) measurements and provides an estimate of the soil moisture within 3-km grid cells (Kim et al., 2014a, 2014b), 3) L2SMAP utilizes SMAP radar measurements to disaggregate the radiometer measurements and provides an estimate of the soil moisture within 9-km grid cells before retrieving soil moisture (Entekhabi et al., 2014; Das et al., 2016). The products are gridded on 36-km, 9-km and 3-km (nested) Equal-Area Scalable Earth grid ver. 2 (EASE-2), respectively. The products are swath based and produced separately. A daily Level 3 composite product is generated from each of the products as well. It is recognized that the sensing depth of a microwave instrument varies depending on the soil moisture content and its distribution (Njoku and Kong, 1977; Escorihuela et al., 2010). Accounting for this effect in

Table 1
SMAP Data Products. Grid-column refers to the resolution of the posting grid and Radar-column indicates whether the product time-series is limited by the radar data availability.

Data product short name	Short description	Grid	Radar
L1BS0_LoRes	Radar backscatter in time order	N/A	X
L1BTB	Radiometer brightness temperature in time order	N/A	
L1CS0_HiRes	High resolution radar backscatter (half orbit, gridded)	1 km	X
L1CTB	Radiometer brightness temperature (half orbit, gridded)	36 km	
L2SMA	Soil moisture (radar, half orbit)	3 km	X
L2SMP	Soil moisture (radiometer, half orbit)	36 km	
L2SMAP	Soil moisture (combined radar and radiometer, half orbit)	9 km	X
L3FTA	Freeze/thaw state (radar, daily composite)	3 km	X
L3SMA	Soil moisture (radar, daily composite)	3 km	X
L3SMP	Soil moisture (radiometer, daily composite)	36 km	
L3SMAP	Soil moisture (combined radar and radiometer, daily composite)	9 km	X
L4SM	Soil moisture model assimilation product (surface and root zone)	9 km	
L4C	Carbon net ecosystem exchange model assimilation product	9 km	

the data product would introduce another set of uncertainties and, therefore, the mission chose to specify the products so that they provide an estimate of the soil moisture in the top 5 cm of the soil (O'Neill et al., 2014). In other words, the uncertainty caused by the variable sensing depth is embedded within the products. Hence, the validation of the products is done with respect to in situ measurements that also provide an estimate for the top 5 cm of the soil with their own set of uncertainties (see Section 5.1). The SMAP satellite is in a 6 AM/6 PM sun-synchronous high-inclination orbit; thus, making measurements in the morning and evening. The primary objective of SMAP is to retrieve soil moisture from the morning overpasses, and therefore, in this paper only the soil moisture retrievals from the morning overpasses are included.

The products include several flags that indicate the quality of the data and the reason for any issues with the quality. The two main flags are the Retrieval Quality Flag (RQF) and Surface Flag (SF). The SMAP baseline retrieval domain is defined by the requirements of the mission: surfaces with permanent ice and snow, urban areas, wetlands, and vegetated areas with vegetation water content >5 kg/m^2 (mostly forests) are flagged (O'Neill et al., 2014; Kim et al., 2014b; Entekhabi et al., 2014). This information is included in the SF along with flags for precipitation and proximity of large waterbody or coast. Fig. 1 shows the global domain where it is expected that the requirements are met. The RQF includes a summary flag indicating whether the use of the data is recommended or not recommended. The use of the data may be not recommended for several reasons: the SF may indicate that the location in question is not suitable for retrieval, the instrument data are flagged for some reason, or the soil moisture algorithm has failed to converge to a solution. In the SMAP validation, only the data recommended by the RQF are used for calculating the performance metrics. The mission requirement for the surface soil moisture for the 36-km and 9-km gridded products is an unbiased root mean square error (ubRMSE) of 0.04 m^3/m^3 within the retrieval domain. The origin of the SMAP soil moisture measurement requirements lies in the analyses carried out before the canceled Hydros mission which adopted similar requirements (Entekhabi et al., 2004). The main assumption is that on one hand a measurement system such as SMAP would be capable of retrieving at this accuracy based on the field experiments (e.g., Jackson et al., 1999) and modeling exercises (Njoku et al., 1999) and on the other hand, a soil moisture product at this level of accuracy provides useful data for various applications and community research (e.g., Entekhabi et al., 2010b). Leading up to the SMAP launch these evaluations were updated several times but the main conclusions remained the same. In general, the way these kinds of requirements are derived depends on mission priorities and each mission makes their own judgement what is called for.

In accordance with the SMAP mission timeline, the preliminary beta version of the Level 1 instrument products was released in July 2015 and the validated version was released in October 2015 together with the preliminary version of the L2–L4 products. The validated surface soil moisture products were released in April 2016. The SMAP data products are distributed by the NSIDC (National Snow and Ice Data Center; http://nsidc.org) and ASF (Alaska Satellite Facility; http://asf.alaska.edu) NASA Distributed Active Archive Centers (DAAC). ASF is responsible for distributing the radar L1 data products and the NSIDC is responsible for the rest of the products.

3. SMAP Cal/Val approach

The primary validation reference data for the SMAP soil moisture data products are ground-based measurements. Well characterized sites with calibrated in situ measurements are used to determine the quality of the data products; these sites are designated as core validation

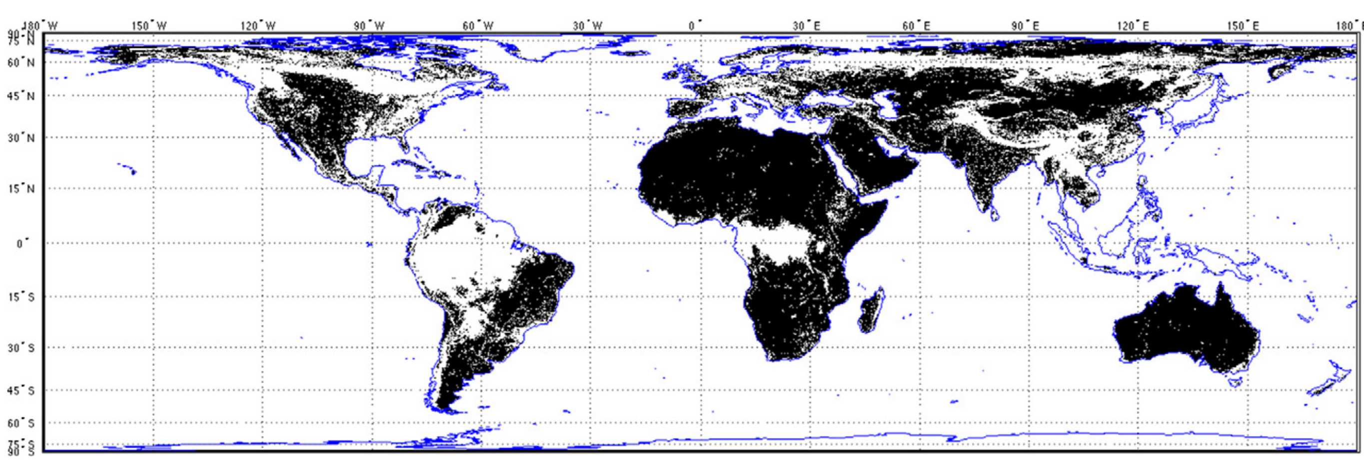

Fig. 1. The areas where SMAP is expected to meet its soil moisture retrieval accuracy requirement are masked with black (surfaces with permanent ice and snow, urban areas, wetlands, and vegetated areas with vegetation water content >5 kg/m2 are excluded).

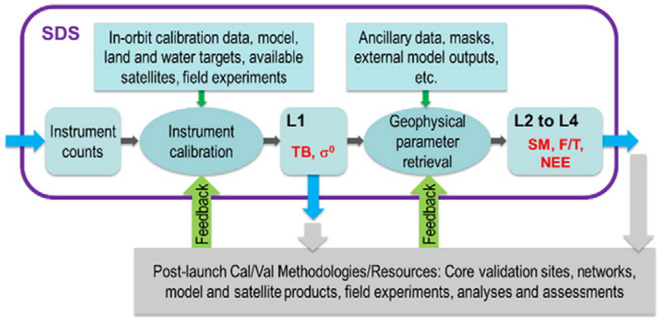

Fig. 2. Overview of the SMAP Cal/Val process. SDS stands for SMAP Science Data System. SDS receives the instrument from the satellite and outputs L1–L4 data products. Additionally, SDS uses other data sources in the processing as indicated in the square boxes. Level 1 data products (brightness temperature, T_B; normalized radar cross-section, σ^0) are calibration and validated using cold sky, earth targets and comparisons to other satellite instruments. The results from these analyses are fed back to SDS for adjusting the algorithms. Level 2 through Level 4 data products (soil moisture, SM; freeze/thaw state, F/T; net ecosystem exchange, NEE) are calibrated and validated using core validation sites, sparse networks, field experiments, other satellite data products, and model-based products. Again, the results from these analyses are fed back to SDS for adjusting the algorithms.

sites. The mission success is evaluated with respect to these core site comparisons. Sparse network measurements (Chen et al., 2016) and other remote sensing (Burgin et al., 2017) and model-based products are used as additional resources to expand the spatial and temporal scope of the validation (Jackson et al., 2013). Fig. 2 shows a schematic diagram of the SMAP Cal/Val process. The SMAP acquisitions are downlinked and transferred to the SMAP Science Data System where the instrument counts are processed for geophysical data retrieval. During the Cal/Val phase of SMAP, there are two main objectives that apply to each science data product: (1) calibrate, verify and improve the performance of the science algorithms, and (2) validate accuracies of the science data products with respect to the mission science requirements and within the mission timeline.

One of the main challenges in fulfilling the Cal/Val tasks for the soil moisture products is incorporating all reference data from the Cal/Val Partners and other sources in the process, while satisfying the mission timeline for validation and data product release. Therefore, the preparation for the intensive period of calibration and validation activities included two rehearsals for exercising Cal/Val methodologies and operational aspects of the data processing and analysis. The second rehearsal ended about six months before the launch of the SMAP satellite, which left time for final remedies and updates before the start of the post-launch Cal/Val activities of the mission. One of the key elements of the rehearsals was setting up automated near-real time data transfers from the in situ sites operated by the SMAP Cal/Val Partners and the utilization of these data in comparisons with simulated SMAP data. This activity resulted in a mature system for making rapid assessments of SMAP products over the Cal/Val Partners' sites. Another important aspect of the rehearsals was to determine the locations of the validation grid pixels in co-operation with the Cal/Val Partners (see Section 5.2).

4. Soil moisture core validation sites

In an effort to ensure the geographic distribution and diversity of conditions of the core validation sites, SMAP partnered with investigators around the globe. These Cal/Val Partners play a crucial role in the execution of the SMAP Cal/Val Plan (Jackson et al., 2013). The core validation site candidates were selected based on a minimum requirement of continuous soil moisture measurements at 5 cm depth with replication within a SMAP grid cell of at least one of the SMAP spatial scales (some sites have multiple pixels at 9-km and 3-km scale). Table 2 lists all the candidates and Fig. 3 shows their location. The sites are divided into two categories: (a) those where confidence in the representativeness of a site at a certain spatial scale is high enough for using the site as a basis of computing the performance metrics (CVS); and, (b) sites that can be utilized for algorithm testing but the confidence of the representativeness is not high enough for using the site in the metrics computations (candidate sites). The detailed criteria for determining whether a site is a CVS are listed below:

1. Number of sensors within the pixel (see Section 5.1)
2. Geographical distribution of sensors within the pixel (see Section 5.1)
3. Calibration of the soil moisture sensors
4. Quality assessment of the measured soil moisture time-series
5. Spatial up-scaling function (see Section 5.1)
6. Maturity as a large scale reference

Sites that initially did not meet these requirements have the option of performing supplemental investigations over time to eventually reach CVS status. For most of the sites (Kuwait, Niger, Benin, Tabasco, Saariselkä, Bell Ville, EURAC, TERENO and Mpala) the main issue was that there was not enough sensors within the pixel. In many of these cases, however, this problem could be alleviated with modeling studies supported by field sampling of limited duration. In particular, sites such as Kuwait, which have homogeneous land cover could credibly estimate average soil moisture with a reduced number of stations (see Section 5.1). In the case of Maqu, Naqu and Ngari the main problem was that the time-series available were only up to June–July 2015 at the time of making this assessment. HOAL and Tonzi Ranch provide clusters of tens of stations, but their geographical distribution does not support upscaling without additional efforts (in both cases upscaling proposals exist but they were not validated by the time of making this assessment). Finally, the Sodankylä site (and also Saariselkä) suffers from the distortion of the EASE grid at higher latitudes. The very elongated pixels do not match well with the SMAP footprint, which complicates the interpretation of the comparison results. It should be emphasized that the limitations at these sites do not mean that the comparisons with respect to SMAP products would result in poor metrics. In fact, in several cases the metrics are quite favorable to SMAP. However, because the criteria set for the CVS before the launch were not met at the time of this analysis the sites are not included in the computation of the performance metrics. Because different SMAP surface soil moisture products have different spatial scales, the suitability of the various sites for validation of the different products must be evaluated separately. Currently qualified core validation sites represent land cover types that together extend over about 70% of the retrieval domain defined for the products (see Section 2). Upgrading some of the current candidate sites to CVS status would raise this figure to close to 100%.

Several of the sites have been used in the validation of other satellite-based soil moisture products in previous investigations, but many of the sites are new (i.e., TxSON and Kuwait) or have not been used for validation before. Several of the USDA-ARS (United States Department of Agriculture-Agricultural Research Service) experimental watersheds have a relatively long history of being used as validation sites for large-scale microwave radiometer based soil moisture products, e.g., (Jackson et al., 2010; Jackson et al., 2012; Rondinelli et al., 2015; Bindlish et al., 2015). Also, sites in Canada (Champagne et al., 2010; Gherboudj et al., 2012; Pacheco et al., 2015), Germany (Montzka et al., 2016), Spain (Sanchez et al., 2012), the Netherlands (Dente et al., 2012a), West-Africa (Louvet et al., 2015), Tibet (Su et al., 2011, 2013; Dente et al., 2012a, 2012b; Zeng et al., 2015, 2016), Mongolia (Jackson et al., 2004; Wen et al., 2014) and Australia (Peischl et al., 2012; van der Schalie et al., 2015; Wu et al., 2015; Yee et al., 2016) have been used for validation studies of satellite-based soil moisture products.

Table 2
List of SMAP soil moisture core validation sites and candidate sites. Sites marked with asterisk (*) were qualified for core validation site status for at least one of the SMAP spatial scales (3 km, 9 km, 36 km) at launch and sites marked with double asterisk (**) have been qualified for core validation site status after launch.

	Site name	Site PI	Location	Core site scales [km][a]	Climate regime[b]	IGBP[c] land cover	References
1	Tonzi Ranch	M. Moghaddam	USA (California)	–	Temperate	Savannas woody	
2	Walnut Gulch*	D. C. Goodrich	USA (Arizona)	3, 9, 36	Arid	Shrub open	(Keefer et al., 2008)
3	Reynolds Creek*	M. Seyfried	USA (Idaho)	9, 36	Arid	Grasslands	(Seyfried et al., 2001)
4	TxSON**	T. Caldwell	USA (Texas)	3, 9, 36	Temperate	Grasslands	
5	Fort Cobb*	P. J. Starks	USA (Oklahoma)	36	Temperate	Grasslands	
6	Little Washita*	P. J. Starks	USA (Oklahoma)	9, 36	Temperate	Grasslands	(Cosh et al., 2006)
7	South Fork*	M. H. Cosh/J. Prueger	USA (Iowa)	3, 9, 36	Cold	Croplands	(Coopersmith et al., 2015)
8	St. Josephs*	S. Livingston	USA (Indiana)	9	Cold	Croplands	
9	Little River*	D. Bosch	USA (Georgia)	3, 9, 36	Temperate	Cropland/natural mosaic	(Bosch et al., 2007)
10	Millbrook	M. Temimi	USA (New York)	–	Cold	Forest deciduous broadleaf	
11	Kenaston*	A. Berg	Canada	3, 9, 36	Cold	Croplands	(Rowlandson et al., 2015)
12	Carman*	H. McNairn	Canada	9, 36	Cold	Croplands	(McNairn et al., 2015)
13	Casselman*	H. McNairn	Canada	9	Cold	Croplands	
14	Tabasco	J. Ramos	Mexico	–	Tropical	Croplands	
15	Monte Buey*	M. Thibeault	Argentina	3, 9, 36	Arid	Croplands	
16	Bell Ville	M. Thibeault	Argentina	36	Arid	Croplands	
17	REMEDHUS*	J. Martínez-Fernández	Spain	9, 36	Temperate	Croplands	(Martinez-Fernandez and Ceballos, 2005)
18	Valencia*	E. Lopez-Baeza	Spain	3, 9	Arid	Savannas woody	
19	EURAC	C. Notarnicola	Italy	–	Polar	Shrub open	(Pasolli et al., 2015)
20	Twente*	Z. Su	The Netherlands	36	Temperate	Cropland/natural mosaic	(Dente et al., 2012a)
21	TERENO	C. Montzka	Germany	–	Temperate	Forest mixed	(Zacharias et al., 2011)
22	HOAL	M. Vreugdenhil/W. Dorigo	Austria	–	Temperate	Mixed forest	(Blöschl et al., 2016)
23	Sodankylä	J. Pulliainen	Finland	–	Cold	Savannas woody	(Rautiainen et al., 2012; Ikonen et al., 2015)
24	Saariselkä	J. Pulliainen	Finland	–	Cold	Savannas woody	
25	Kuwait	H. Jassar	Kuwait	–	Temperate	Barren/sparse	
26	Mpala	K. Caylor	Kenya	–	Temperate	Grasslands	
27	Niger	T. Pellarin	Niger	–	Arid	Grasslands	(Louvet et al., 2015)
28	Benin	T. Pellarin	Benin	–	Arid	Savannas	(Louvet et al., 2015)
29	Ngari	Z. Su	Tibet	–	Arid	Barren/sparse	(Su et al., 2011, 2013)
30	Naqu	Z. Su	Tibet	–	Polar	Grasslands	(Su et al., 2011, 2013)
31	Maqu	Z. Su	Tibet	–	Cold	Grasslands	(Su et al., 2011, 2013)
32	Mongolian grasslands**	J. Asanuma	Mongolia	36	Cold	Grasslands	(Wen et al., 2014)
33	Yanco*	J. Walker	Australia	3, 9, 36	Semi-Arid	Croplands/Grasslands	(Panciera et al., 2014)
34	Kyeamba*	J. Walker	Australia	36	Temperate	Croplands	(Smith et al., 2012)

* Core site status at launch.
** Core site status acquired after launch.
[a] Empty means that the site is not core site at any scale currently (but this may change in the future).
[b] Koeppen-Geiger climate classification (Peel et al., 2007).
[c] International Geosphere-Biosphere Program.

As an example, Fig. 4 shows the layout of the site stations and the SMAP grid for the TxSON, Little Washita and Kenaston 36-km reference pixels. Because TxSON was developed after the SMAP grid was established, the in situ measurements are geographically distributed within the SMAP pixel. Conversely, the networks at Little Washita and Kenaston were established prior to SMAP and their station distribution is not aligned with the SMAP standard grid. In order to fully exploit the available sampling at these sites a special validation grid processor (the black rectangle) was developed (Section 5.2) for L2SMP comparison. Fig. 5 shows the site layout and the SMAP grid for one of the TxSON and the Monte Buey 9-km pixels for L2SMAP comparison. Fig. 6 shows the site layout and the SMAP grid for TxSON and Yanco 3-km pixels for L2SMA comparison.

5. Matching SMAP data with the core sites

Four aspects of matching the SMAP soil moisture products are discussed in this section: 1) estimating the average soil moisture within the reference pixels based on the in situ measurements i.e. spatial up-scaling; 2) matching the SMAP soil moisture processing with the location of the in situ stations; 3) processing of the in situ measurements for the match-up processing, and 4) computation of the metrics based on the comparison.

5.1. Up-scaling of reference pixels

The idea of the CVS is that they provide reference pixels where the average soil moisture can be estimated with confidence at the various SMAP spatial scales. Basically this means adequate replication of in situ measurements with a representative distribution within the pixel. The objective is to capture the spatial heterogeneity of soil moisture so that the estimate based on the in situ measurements corresponds to the product grid size at which the remotely sensed estimate is made. The soil moisture heterogeneity is driven by precipitation distribution, topography, soil texture and land cover. In general, the in situ sampling requirement can be derived based on typical soil moisture variability. In Famiglietti et al. (2008) soil moisture variability was estimated based upon several field experiments across a range of scales. Using these results SMAP specified that a 36-km CVS should have at least 8 stations (70% confidence for 0.03 m^3/m^3 soil moisture uncertainty with 0.07 m^3/m^3 variability), a 9-km core site at least 5 stations (70% confidence for 0.03 m^3/m^3 soil moisture uncertainty with 0.05 m^3/m^3

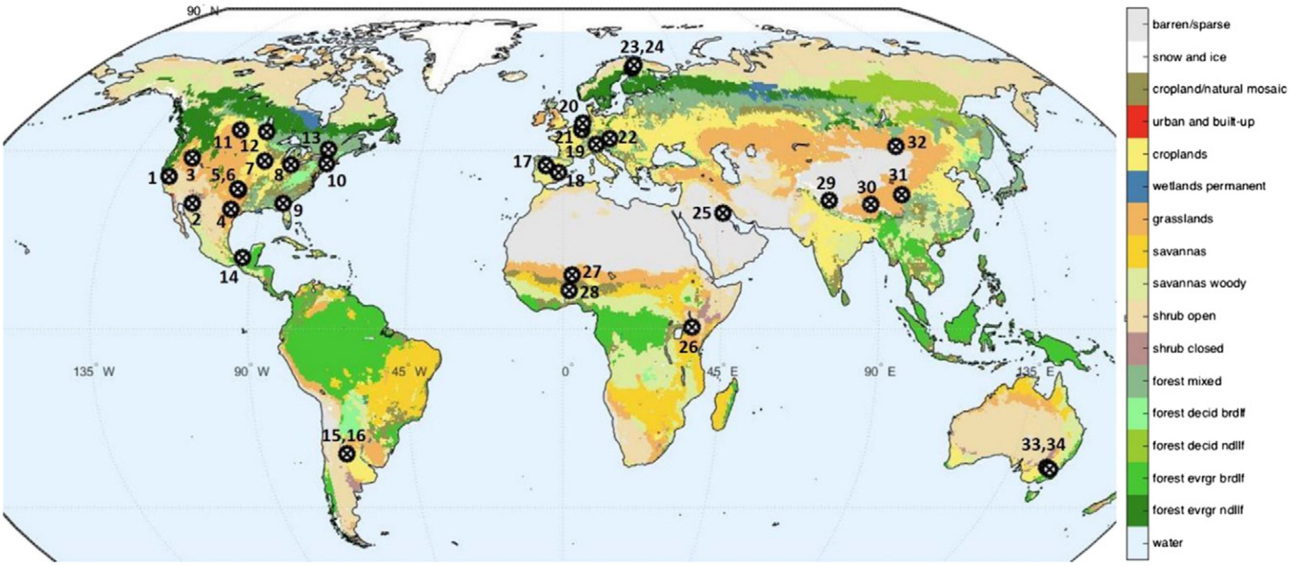

Fig. 3. Location of all SMAP soil moisture core validation site candidates with the IGBP-based land cover classification as the background.

variability), and a 3-km core site at least 3 stations (70% confidence for 0.05 m^3/m^3 soil moisture uncertainty with 0.05 m^3/m^3 variability). Table 3 shows the number of stations at each 36-km core site; the majority of sites exceed 17 stations, resulting in 90% confidence for 0.03 m^3/m^3 soil moisture uncertainty with the same parameters.

The quality of the in situ data from individual points can be improved by a location-specific calibration of the in situ sensor instead of the generic factory calibration, e.g., (Cosh et al., 2005; Burns et al., 2014). It was also recommended that limited field campaigns be conducted at all sites to acquire gravimetric samples of the 0–5 cm layer at in situ measurement locations as well as at additional locations, e.g., (Adams et al., 2015). This would contribute to reducing uncertainty associated with calibration (using a 5-cm depth sensor to represent a 0–5 cm layer) and up-scaling the network to the grid.

With regard to spatial up-scaling, unless the in situ measurements are dense and evenly spread across the site, using the arithmetic average of the measured values does not guarantee an accurate estimate of the grid average soil moisture. Different techniques can be used to determine the representativeness of the stations with respect to the average of the pixel and how to weight the stations to obtain an accurate estimate of the average soil moisture. The default approach selected by SMAP is to use a Voronoi diagram to find the weighting of the stations. The Voronoi diagram technique partitions a plane into regions based on the distance of a set of points to each other within a bounded area (Voronoi, 1908; or see Thiessen Polygons in Dingman, 2015). Another approach to up-scaling is to use land surface modeling. In this scheme the idea is to relate the soil moisture anomaly determined from the in situ sensors to the anomaly determined from a high-resolution model. Models have the ability to capture features within the domain that occur at locations not covered by the sensors. By using the anomaly soil moisture the effect of these features may be added to the in situ average without influencing the measurement based average significantly (van der Velde et al., 2016).

Each of the up-scaling techniques noted above can be used in soil moisture validation 1) to account for the spatial soil moisture variability within the large scale pixel, and 2) to prevent overemphasis of areas with denser distribution of stations. Fig. 7 shows the Voronoi diagram for the Yanco and REMEDHUS sites. The diagrams illustrate the different weighting parameters based on the geometric distribution of the stations within the pixel. In the case of Yanco the stations clustered in

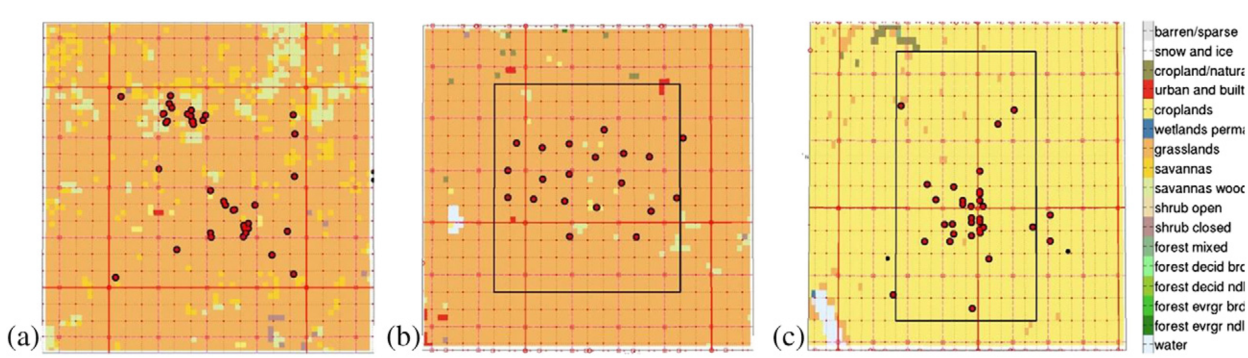

Fig. 4. (a) TxSON, (b) Little Washita and (c) Kenaston 36-km reference pixels. The thick red lines mark the 36-km grid; the dashed magenta lines mark the 9-km grid, and the thin dotted lines mark the 3-km grid. Because of the global EASE grid the shape of the grid pixels are elongated at the latitude of Kenaston site. The black boxes mark the validation grid pixel (see Section 5.2). The background is the IGBP land cover classification which is also used by the algorithms for distinguishing between different land cover types. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

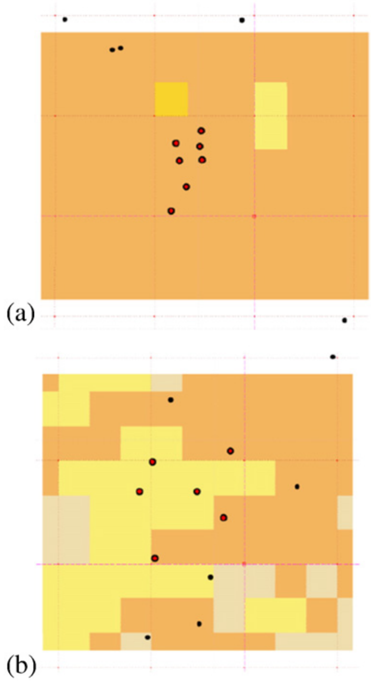

Fig. 5. (a) TxSON and (b) Monte Buey 9-km reference pixels. Stations marked with red are used for computing the up-scaled soil moisture. The marking of the grid lines is the same as in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

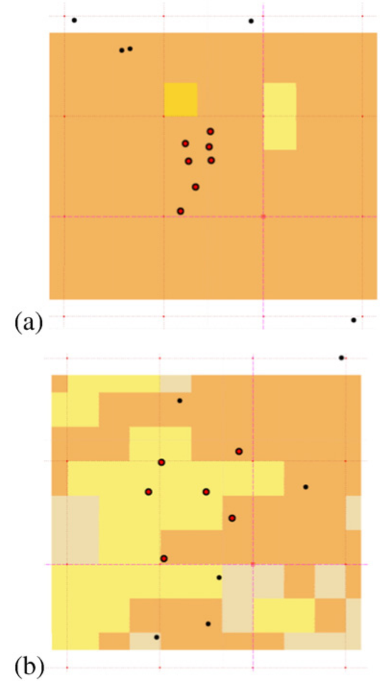

Fig. 6. (a) TxSON (0302) and (b) Yanco YA4 (0301) 3-km reference pixels. Stations marked with red are used for computing the up-scaled soil moisture. The marking of the grid lines is the same as in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the corners (for providing replication at 9-km and 3-km scales) receive appropriate weight in terms of the spatial average with respect to the points in the center. Another approach that can be used involves the use of soil texture and land cover to determine the representative area of the measurement of each station (Bircher et al., 2012; Dente et al., 2012b). As an example, this technique was used for the Carman site, which has a large soil texture gradient within the pixel that would not be well represented with one of the aforementioned weighting schemes (Pacheco et al., 2015). As noted previously, in analyzing and verifying an up-scaling approach, additional dense ground sampling and high resolution airborne measurement of the pixel are very helpful. The data can be used to establish the temporal stability of the measurement stations for estimating their representativeness of the pixel average (Vachaud et al., 1985; Cosh et al., 2006; Starks et al., 2006). The most stable stations could also be used as the reference for the pixel. The drawback of the method is the fact that even though the location may be statistically representative, anomalous event such as uneven drying or wetting of the area can cause uncertainty in the estimation based on that one location (see Section 7). In some cases a straight average of the station measurements is justified. In the case of SMAP, this applies mostly to the candidate sites where there is no basis for more sophisticated scaling approach, yet there may be some benefits in analyzing the data for algorithm development. Finally, the selection of the scaling approach depends also on the scale of the pixel and the prevailing precipitation patterns in the area.

5.2. Validation grid processing for the passive soil moisture product

The standard SMAP grid does not always align perfectly with each of the core site domains, which adds to the uncertainty when using the products on the standard grid in comparisons to core sites. Most of the sites were established to satisfy objectives related to various research programs rather than to match the measurement locations with the SMAP standard grid. When examining the distribution of points at sites it was found that in many cases only a few points fell in any specific standard grid pixel, which could lead to many sites being rejected due to inadequate replication. The problem is compounded with the 36-km scale, because of the higher probability of significant spatial variability of precipitation within the 36-km pixel. In order to match the site measurements with the SMAP retrievals so as to exploit the largest number of locations, a special processing stream was established called validation grid processing. The validation grid processing allowed retrieval of soil moisture centered at any location defined by the intersection of the SMAP 3-km grid lines using re-gridding of the brightness temperature and the standard L2SMP soil moisture retrieval algorithms. Therefore, computationally the validation grid product is the same as

Table 3
Upscaling approach of the 36-km core sites.

Site name	Number of stations*	Up-scaling approach
Walnut Gulch	29	Voronoi diagram based weights
Reynolds Creek	20	Voronoi diagram based weights
TxSON	36	Voronoi diagram based weights
Fort Cobb	15	Voronoi diagram based weights
Little Washita	20	Voronoi diagram based weights
South Fork	20	Voronoi diagram based weights
Little River	28	Voronoi diagram based weights
Kenaston	28	Voronoi diagram based weights
Carman	9	Soil type and land cover based weights
Monte Buey	14	Voronoi diagram based weights
REMEDHUS	19	Voronoi diagram based weights
Twente	5	Model-based scaling function
Mongolian grasslands	7	Arithmetic average
Yanco	28	Voronoi diagram based weights
Kyeamba	5	Arithmetic average

* This refers to number of stations used in the computation of the up-scaled value, not necessarily to the total number of stations within the pixel (because, for example, there could have been a problem with a station or stations during the evaluation period).

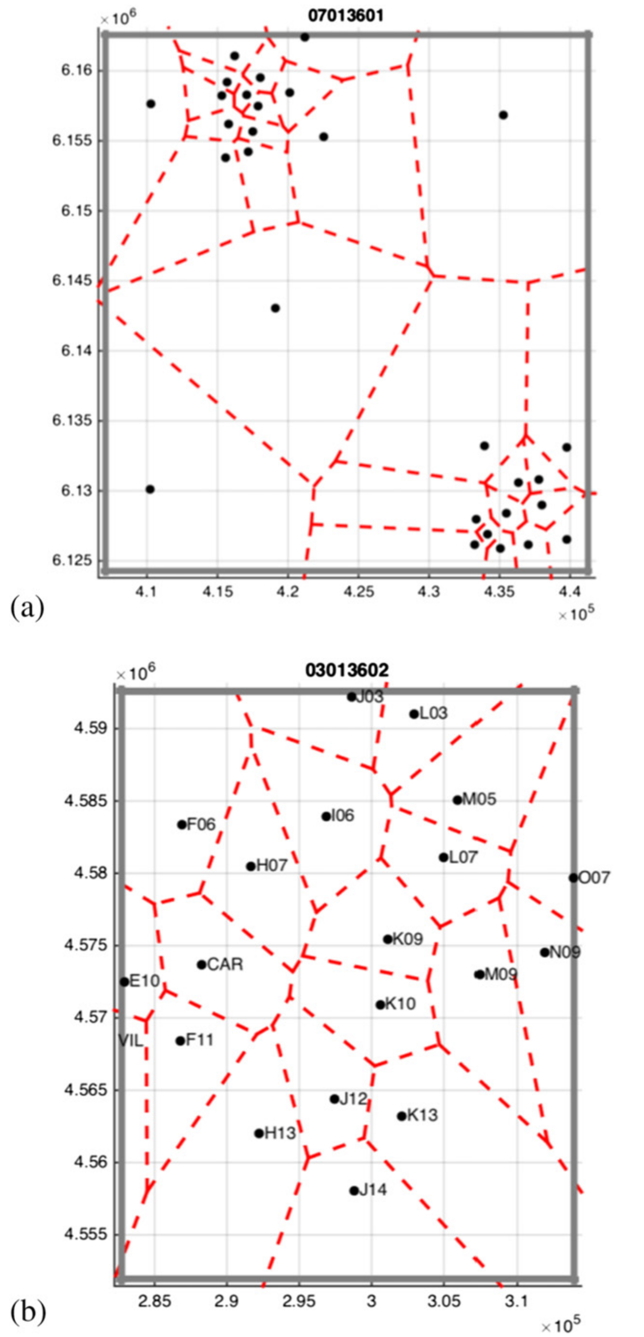

Fig. 7. Two examples of Voronoi diagrams used for weighting the in situ measurements: (a) Yanco, Australia, 36-km grid cell, and (b) REMEDHUS, Spain, 36-km grid cell. The images are plotted on the UTM (Universal Transverse Mercator) projection.

the standard L2SMP product, with the validation grid including all of the original standard grid pixels.

The selection of a certain validation grid pixel location for each site was done collaboratively with the Cal/Val Partners before the launch of the mission. Fig. 4a shows the validation grid positioning for the Little Washita and Kenaston sites. The validation grid increases the number of stations that can be used as well as improves their geographic distribution with respect to the pixel. Other considerations behind the selection of the validation grid include avoiding or minimizing the effects of land features that were not representative of the sampled domain or were known to introduce problems during the soil moisture retrieval (i.e. water bodies). Fig. 8 shows the validation grid pixel for the Fort Cobb site. In this case the positioning avoids a reservoir on the south side of the stations, and optimizes the representativeness of the stations with respect to the land type (soil texture and land cover). The pixel is oriented more to the west because the west side corresponds better to the land type covered by the stations.

5.3. Matchup data processing

The processing of the in situ data provided by the Cal/Val Partners goes through several steps before matching up with the SMAP products. Fig. 9 shows the flow of the data with each of the processing steps. The Cal/Val Partners update the data at a 1–30 day frequency in most cases and SMAP pulls the data from the Cal/Val Partners automatically. The data are run through an automatic quality control (QC) procedure before determining the up-scaled soil moisture values for each pixel. The QC is implemented largely following the approach presented in (Dorigo et al., 2012). The procedure includes checks for missing data, out of range values, spikes, sudden drops and physical temperature limits. Additionally, the physical temperature is checked to be above 4 °C because some sensors begin to exhibit unpredictable behavior below this threshold. Finally, stations deemed not to represent the surrounding environment are excluded. This may be done, for example, based on irrigation activities or location of the station. The up-scaling function discussed in Section 5.1 is then applied to the data. The up-scaling function is developed using the set of sensors that function properly the majority of the time period under consideration. This means that the Voronoi diagrams are determined using the functioning sensors only and the sensors that fail during the time period are left outside the process entirely. Coincident overpasses, in time and space, are then matched up with the up-scaled in situ time-series. The in situ observation closest to the overpass time is used. The matchup processing includes SMAP data product flags RQF and SF. The high-level of automation in this process allows tracking of the performance of the soil moisture products periodically and with low latency because repetitive manual involvement is minimized. The matchup products are used for the validation and further development of the algorithms. It has been of great value to the SMAP Cal/Val process to have data with low latency and automatic delivery. However, there are sites that are constrained to less frequent delivery. An example of this is Mongolia where a team physically downloads the data once a year; yet these data are still valuable to the overall Cal/Val process.

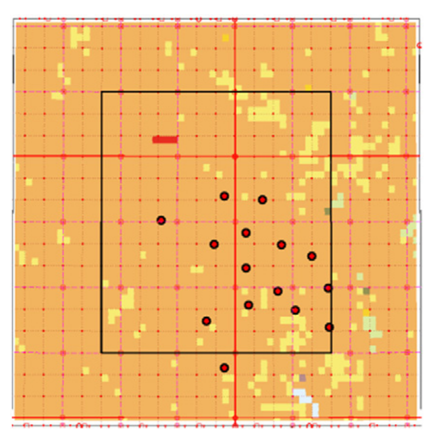

Fig. 8. Fort Cobb 36-km reference pixel. The light blue pixels in the southeast corner depict a water body. The marking of the grid lines is the same as in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

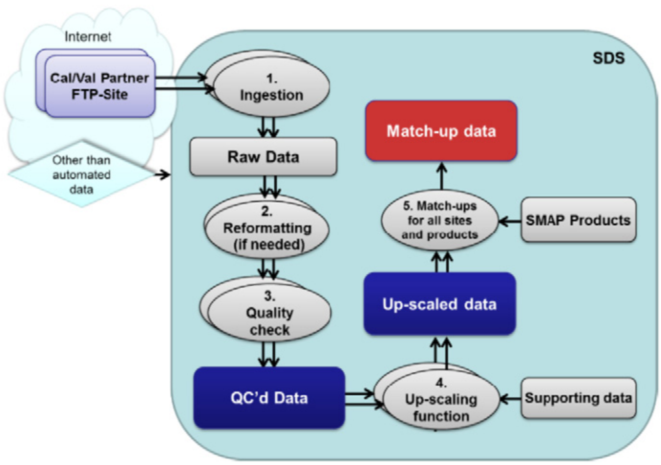

Fig. 9. Diagram of the data flow of the in situ data from the Cal/Val Partners through the processing at SMAP SDS which results in uniformly formatted, quality controlled, up-scaled match-up datasets with the SMAP soil moisture data products.

5.4. Metrics computation

Four metrics are computed over each site: ubRMSE, bias, RMSE and Pearson correlation coefficient (Entekhabi et al., 2010b). The metrics are computed for the up-scaled data points that have no in situ QC flag raised, and where the SMAP product RQF shows recommended status (typically RQF is set to not-recommended if any of the SF is raised). SMAP reports the product uncertainty foremost using ubRMSE, while the rest of the metrics are used to gain additional insight into the performance of the data product and help in further adjustments of the algorithms. The summary of all metrics is presented as the average over the metric value for each core validation site and also as the RMS over the biases determined for each core validation site.

6. Results

6.1. 36-km passive product (L2SMP)

Fig. 10 shows the time-series comparisons of the SMAP passive soil moisture and up-scaled averages for the core validation sites in Texas (TxSON), Canada (Kenaston), Spain (REMEDHUS) and Yanco (Australia). The validation grid processing corresponds to product version R13080. The plots include, in addition to the in situ soil moisture and the SMAP retrieval value, in situ observed precipitation, the flagging of the SMAP product (based on the RQF and SF) and the flagging of the in situ record. The precipitation is the average from the rain gages available within the pixel. The plots show overall good retrieval behavior for the selected sites. For the Kenaston site a large part of the time-series is flagged because of the winter season in Saskatchewan. Over TxSON there is a slight overestimation during the dry period in the fall. In Kenaston some underestimation can be observed throughout the season. For REMEDHUS the dry summer season is marked by some underestimation which disappears with the increased soil moisture in the winter. At Yanco many instances of soil moisture overestimation are associated with precipitation events. It is hypothesized that in some cases a relatively small precipitation just prior to a SMAP overpass results in a wet soil surface but does not reach the depth of the in situ sensors. This gives a false wet soil result. The South Fork site is located in an agricultural area in Iowa dominated by corn and some soybeans. The SMAP product experiences difficulties detecting the soil moisture over this site precisely. The time series shows that the retrieval has both bias issues before the emergence of crops and sensitivity issues when the crops are full grown. The soil moisture is underestimated throughout most of the period. Fig. 11 shows the in situ scatterplots for the same sites used in Fig. 10. The scatterplots also include the performance metrics for these sites. Table 4 lists the performance metrics for all CVS for two time-periods. First, the full time-series metrics are shown. These indicate that the performance is within the mission requirements (ubRMSE < 0.04 m^3/m^3). Overall, the performance is better for sites that are not dominated by cultivated agriculture. The reason for this is likely the highly varying roughness and vegetation conditions over the seasons which are not captured by the models in the retrieval algorithm like displayed over South Fork. The overall bias is assessed both as the average and the RMS value over the results of the individual sites. Second, the metrics are shown for the time-period when the SMAP radar was operating. The second set of metrics compare well with the full time-series metrics. This indicates that the subsequently computed metrics for L2SMAP suggest a similar comparison results over the full time-series, because of the similarities of the retrieval algorithm to that of L2SMP (the difference between the algorithms is the disaggregation of the brightness temperature, which is tested over the radar operation period under highly diverse conditions). Therefore, these results are also relevant to product inter-comparison over the full time-period. The assessment of the L2SMP product with a description of the algorithm is given in detail in (Chan et al., 2016). Furthermore, Colliander et al. (2017) provides further details about the comparison over the Walnut Gulch site using the intensive ground sampling and airborne measurements of SMAP Validation Experiment 2015.

Table 5 shows the metrics for the L2SMP products using arithmetic averaging of the in situ measurements instead of the different weighting schemes (Table 4). The overall mean and RMS metrics are very close to the weighted ones. In some cases the differences are very small but in a few cases they reflect a significant impact of the weighting on the average soil moisture. For sites with a lot of stations the differences are generally small, and unsurprisingly, indicate that arithmetically averaging a set of stations that are well distributed over a site provides a good estimate of the average soil moisture. In several cases the metrics are, in fact, better for the arithmetic case. However, it is still assumed that the weighted approach provides better estimates of the true soil moisture average for the pixel and the arithmetic average just happens to be closer to the SMAP estimate and, therefore, results in better metrics. For example, the Yanco and TxSON sites have clustered stations and the Voronoi diagram unarguably avoids overweighting these areas. For the Yanco case the weighted metrics are better (although bias is slightly better for the arithmetic case) and for the TxSON case it is slightly worse. The main conclusion from the comparison of these different weighting schemes is that the choice of the selected approach does not necessarily result in better metrics for SMAP, but they are expected to provide more reliable estimates of the soil moisture average.

6.2. 9-km active passive product (L2SMAP)

Fig. 12 shows the time-series comparisons of the SMAP L2SMAP soil moisture product and up-scaled averages for the 9-km pixels at the core validation sites in Spain (Valencia) and Australia (Yanco). The L2SMAP features only a limited time-series from April 13 until July 6 because of the radar failure on July 7. Product version corresponds to the validated release R13080. For the Valencia site the L2SMAP performance is nominal. For the Yanco site SMAP overestimates the soil moisture, in particular right after the rain events, similarly to the L2SMP product. This is not unexpected based on the similarities in the retrieval algorithms. Fig. 13 shows the L2SMAP versus the up-scaled in situ scatterplots for the same sites as depicted in Fig. 12. The scatterplots also include the performance metrics derived at the sites. The overestimation associated with the rain events at Yanco is also reflected in the metrics, both in the ubRMSE and bias. Table 6 shows the performance metrics for the 9-km validation pixels (the radar measurements suffer from unfiltered RFI around Midwest region, which is the reason that

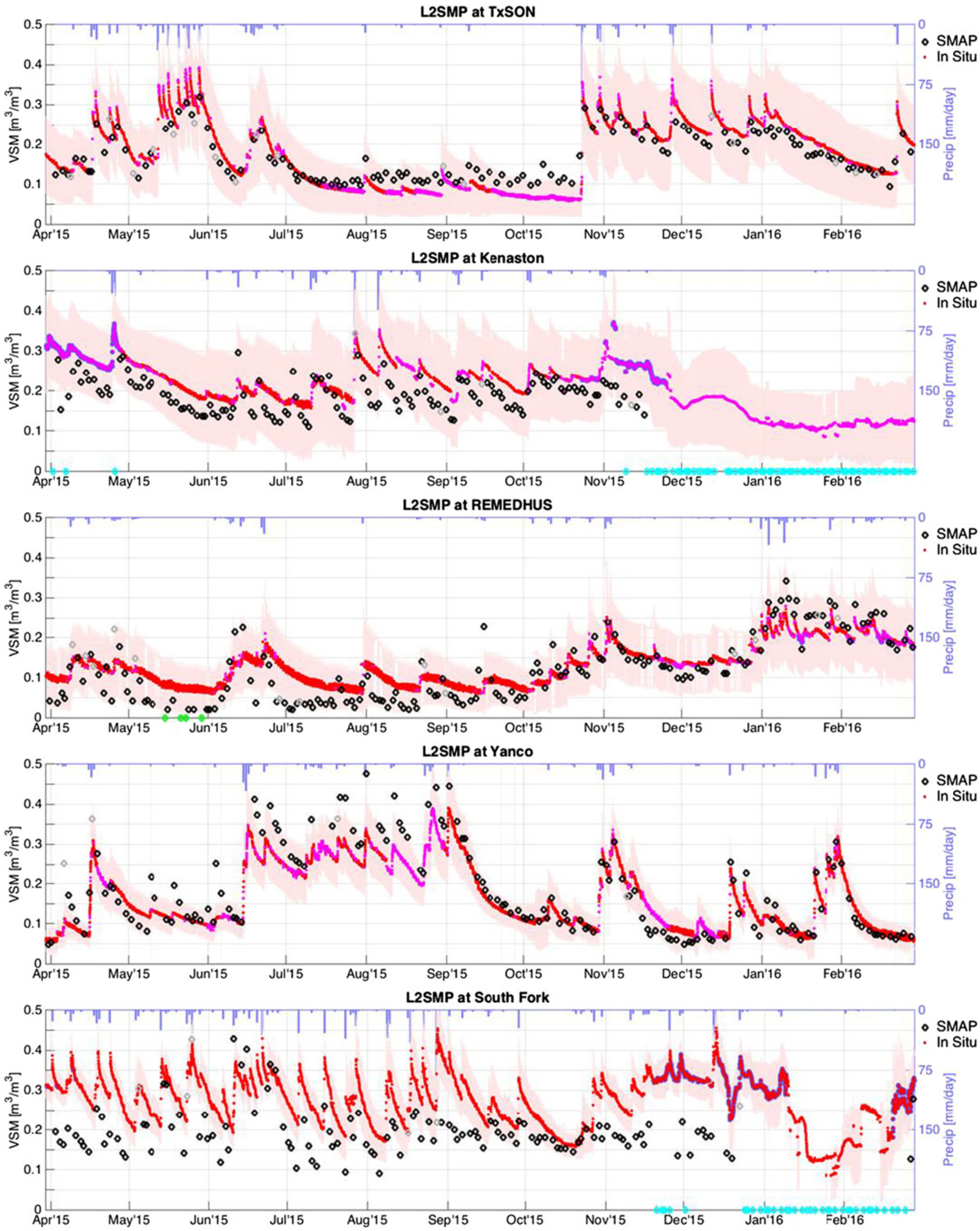

Fig. 10. Time-series comparing SMAP L2SMP soil moisture data product with respect to core validation site averages. The in situ average is the red or magenta continuous line and the SMAP retrievals are marked with black diamonds. Daily precipitation is indicated by the blue bars. The SMAP retrievals are color-coded based on the RQF so that the gray diamonds indicate that the retrieval value is not recommended, the green diamonds indicate that the retrieval failed (at the bottom of the scale), and the light-blue diamonds indicate that the retrieval was not even attempted at the bottom of the scale. The flagged data points are not used for the metrics computation. Nominal in situ measurements are marked with red color and in situ measurements which have quality flag raised are marked with magenta color. The flagged in situ data are not used for the metrics computation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

South Fork and Carman are not included). The ubRMSE is approximately 0.04 m^3/m^3, which is the mission requirement. As discussed in Section 6.1, based on the analysis on L2SMP performance, this result suggests that the product would meet similar performance over the full time period as well.

6.3. 3-km active product (L2SMA)

Fig. 14 shows the time-series comparisons of L2SMA and up-scaled averages for the 3-km pixels at the core validation sites in Canada (Kenaston) and Australia (Yanco). The L2SMA features only a limited

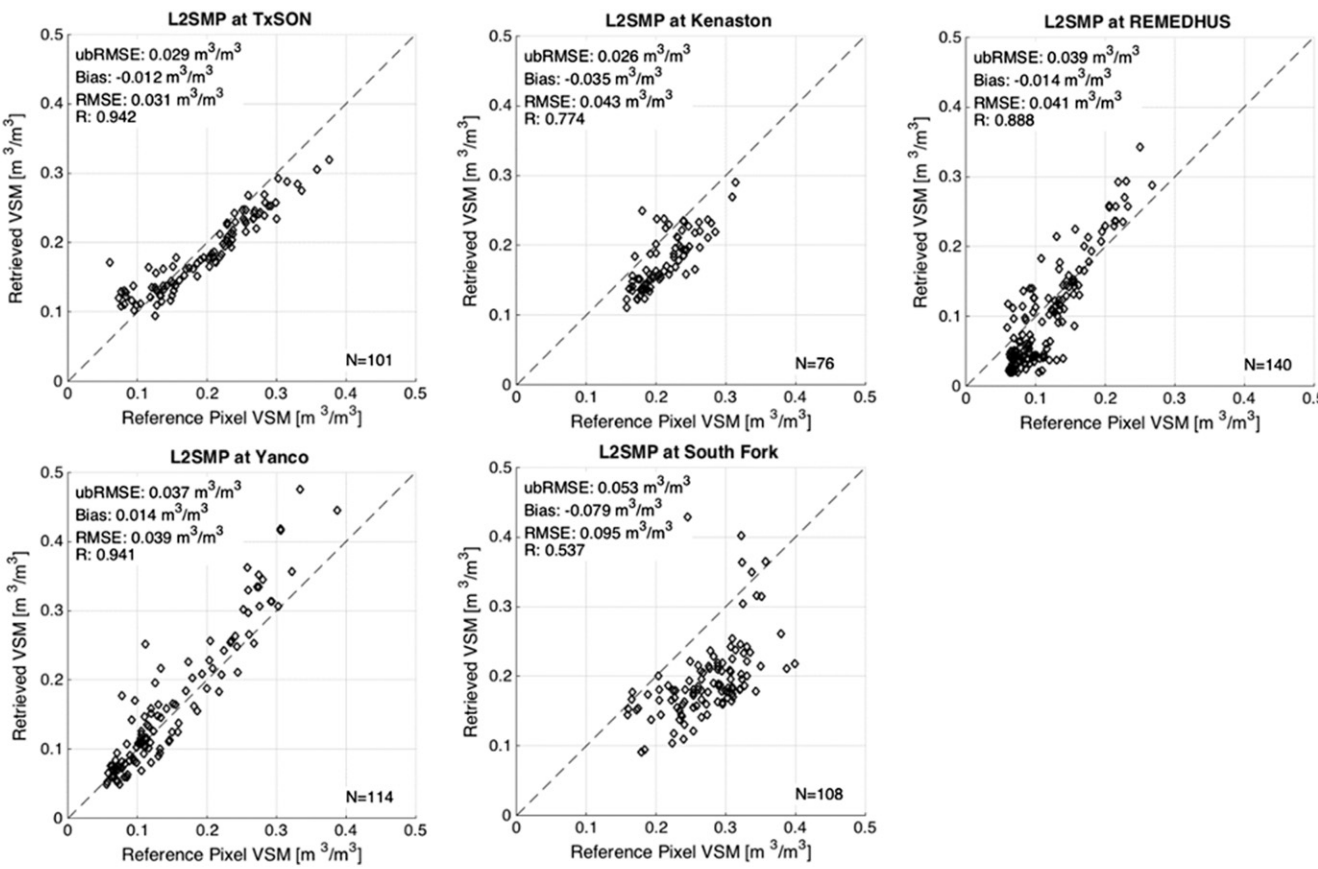

Fig. 11. Scatterplots for the CVS in Texas (TxSON), Canada (Kenaston), Spain (REMEDHUS), Australia (Yanco), and Iowa (South Fork). N means the number of measurement points used in the metrics computation (which excludes all flagged SMAP and in situ values). The data record is the same as used in Fig. 10.

time-series from April 13 until July 6 because of the radar failure on July 7. The product version corresponds to the validated release R13080. For the Kenaston site, crops were seeded in wheat, soybeans and lentils near the end of May 2015. The underestimation by the SMAP retrieval from June is likely due to incomplete correction of the effects of actively growing vegetation effects (Kim et al., 2016). The three incidents of overestimation in early May, mid-June, and early July are coincident with light precipitation that was not recorded at this pixel by the rain gages (not all soil moisture stations at Yanco are equipped with rain gages). This is the same effect observed by L2SMP and L2SMAP. In the L2SMA case, the backscatter is sensitive to the wetness in the top soil while the in situ probes at 5-cm depth detect much less moisture. For

Table 4
The performance metrics for the SMAP 36-km radiometer-based L2SMP product. The metrics on the left-hand side are for an eleven month period and the ones on the right-hand are for the radar operation period. R refers to Pearson correlation.

	Weighted average L2SMP: April 1, 2015–February 29, 2016				Weighted average L2SMP: April 13, 2015–July 6, 2015			
Site name	ubRMSE	Bias	RMSE	R	ubRMSE	Bias	RMSE	R
Reynolds Creek	0.041	−0.030	0.051	0.670	0.029	−0.065	0.071	0.788
Walnut Gulch	0.028	−0.006	0.028	0.688	0.032	−0.010	0.034	0.489
TxSON	0.029	−0.011	0.031	0.942	0.022	−0.021	0.030	0.976
Fort Cobb	0.029	−0.040	0.049	0.883	0.033	−0.046	0.057	0.858
Little Washita	0.020	−0.018	0.027	0.940	0.028	−0.011	0.030	0.903
South Fork	0.053	−0.064	0.083	0.515	0.068	−0.063	0.093	0.499
Little River	0.028	0.095	0.099	0.924	0.023	0.092	0.095	0.912
Kenaston	0.026	−0.035	0.043	0.774	0.026	−0.030	0.040	0.568
Carman	0.058	−0.085	0.103	0.620	0.082	−0.088	0.120	0.597
Monte Buey	0.056	0.013	0.058	0.885	0.022	0.000	0.022	0.969
REMEDHUS	0.039	−0.013	0.041	0.897	0.041	−0.032	0.052	0.701
Twente	0.054	0.035	0.064	0.919	0.042	−0.002	0.042	0.719
Mongolian grasslands	0.037	−0.008	0.037	0.765	0.030	−0.014	0.034	0.704
Yanco	0.037	0.013	0.039	0.936	0.047	0.023	0.052	0.752
Kyeamba	0.054	0.004	0.054	0.948	0.040	0.009	0.041	0.947
AVERAGE	0.039	−0.010	0.054	0.820	0.038	−0.017	0.054	0.759
RMS		0.042				0.045		

Table 5
The performance metrics for the SMAP 36-km radiometer-based L2SMP product computed using arithmetic averaging of the in situ sensors.

	Arithmetic average L2SMP: April 1, 2015–February 29, 2016			
Site name	ubRMSE	Bias	RMSE	R
Reynolds Creek	0.034	−0.029	0.044	0.733
Walnut Gulch	0.027	0.001	0.027	0.711
TxSON	0.026	−0.005	0.026	0.950
Fort Cobb	0.027	−0.033	0.043	0.896
Little Washita	0.021	−0.020	0.029	0.933
South Fork	0.052	−0.087	0.101	0.550
Little River	0.027	0.103	0.106	0.915
Kenaston	0.021	−0.039	0.044	0.854
Carman	0.056	−0.058	0.081	0.677
Monte Buey	0.051	0.002	0.051	0.909
REMEDHUS	0.040	−0.006	0.041	0.878
Twente	0.044	0.014	0.046	0.920
Mongolian grasslands	0.039	−0.008	0.040	0.681
Yanco	0.042	0.010	0.043	0.919
Kyeamba	0.054	0.005	0.055	0.949
AVERAGE	0.037	−0.010	0.052	0.832
RMS		0.042		

the Yanco site where planting occurred before May, the underestimation by SMAP is more pronounced towards July as the vegetation grows (5 to 30 cm tall wheat and pasture), which might not be adequately captured by the climatology. As in the case of the retrievals for Kenaston, incomplete correction of vegetation effect might be responsible.

In summary, for the 13 CVS retrievals, wetting and dry-downs are well captured by radar retrieval, with the correlation coefficient of 0.48 and unbiased RMSE of 0.054 m^3/m^3, the product meets the internal target of 0.06 m^3/m. Generally the statistics for non-croplands are better than those of croplands (ubRMSE of 0.044 vs 0.073 m^3/m^3, Table 7). Croplands pose more challenges as discussed above, notably temporal changes in vegetation and surface roughness, periodic row structure, and diversity of crop types that produce distinctively different scattering mechanisms. It is found that some of the differences in the CVS comparison likely has a non-algorithmic cause such as the discrepancy in sensing depth of radar vs. in situ. Excluding these cases, the ubRMSE improves by a factor of two on each CVS and, since these cases occur on as many as five CVS, the overall ubRMSE is expected to improve. The correlation could improve as well if the arid Walnut Gulch comparisons are excluded where the correlation has little meaning when the soil moisture varies little in time. The assessment of the L2SMA product with a description of the algorithm is given in detail in (Kim et al., 2016).

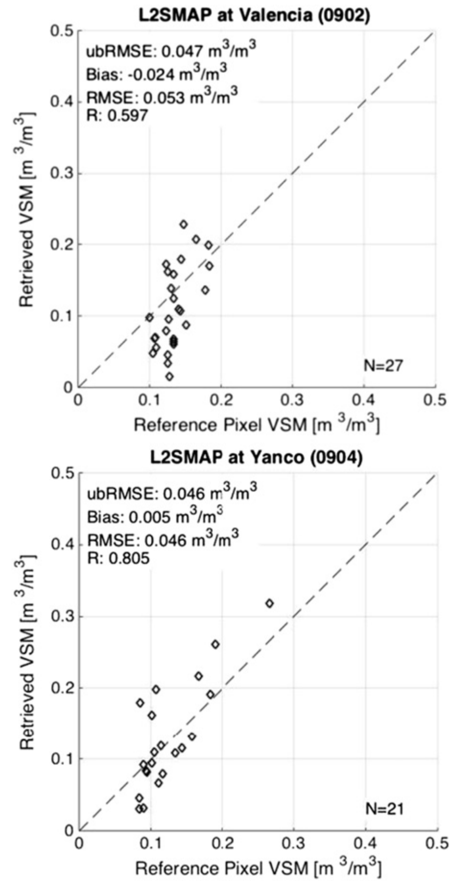

Fig. 13. Scatterplots for the CVS in Spain (Valencia) and Australia (Yanco). N means the number of measurement points used in the metrics computation (which excludes all flagged SMAP and in situ values). The data record is the same as used in Fig. 12.

7. Discussion

The approach to validating soil moisture data products based on core site observations presented above enabled evaluation of the SMAP soil

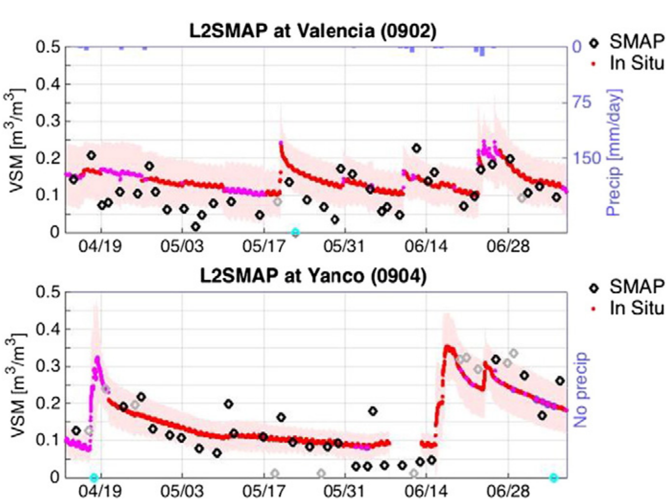

Fig. 12. Time-series comparing SMAP L2SMAP soil moisture data product with respect to core validation site averages (see Fig. 10 caption for symbol definitions).

Table 6
The performance metrics for the SMAP 9-km combined radar-radiometer soil moisture product (L2SMAP). The pixel ID is given in the parenthesis when a site has multiple pixels. R refers to Pearson correlation.

	L2SMAP: April 13, 2015–July 6, 2015			
Site name	ubRMSE	Bias	RMSE	R
Tonzi Ranch	0.030	−0.070	0.076	0.692
Walnut Gulch (0921)	0.038	−0.020	0.043	0.286
Walnut Gulch (0922)	0.018	−0.013	0.022	0.980
TxSON (0902)	0.028	0.031	0.042	0.891
TxSON (0911)	0.039	−0.033	0.051	0.824
Little Washita	0.050	−0.067	0.083	0.728
Little River	0.028	0.050	0.057	0.752
Kenaston	0.059	−0.021	0.063	0.418
Monte Buey	0.047	−0.026	0.054	0.981
Valencia	0.047	−0.024	0.053	0.597
Yanco YA (0903)	0.084	0.075	0.113	0.789
Yanco YB (0904)	0.046	0.005	0.046	0.805
AVERAGE	0.043	−0.009	0.059	0.729
RMS		0.043		

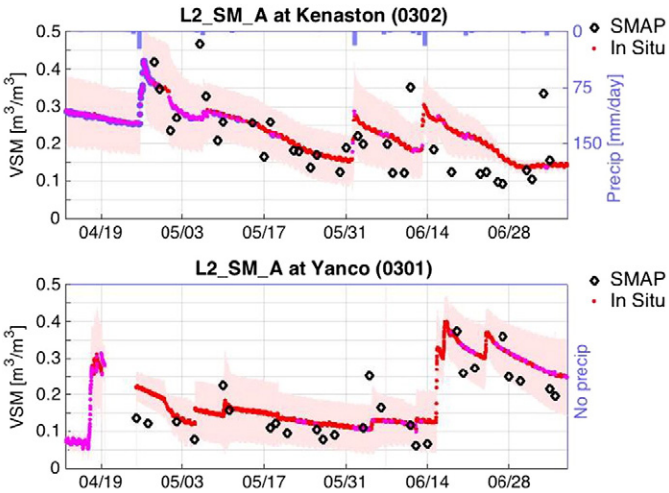

Fig. 14. Time-series comparing SMAP L2SMA soil moisture data product with respect to core validation site averages (see Fig. 10 caption for symbol definitions).

moisture products within a very short time after the actual SMAP data acquisition with high reliability. This allows the tracking of the performance and remedying of problems early on in the mission and eventually meeting the timeline of releasing validated soil moisture products only 12 months after the completion of the in orbit checkout phase. Traditionally, validation programs for satellite missions producing soil moisture data have made tradeoffs between either precision (by using, e.g., point wise sparse network reference data) or timeliness (by conducting core validation site analysis several years into the missions).

An integral part of the calibration/validation process was the screening of the sites meeting the requirements set by SMAP for the soil moisture validation prior to the availability of SMAP data. Out of the 34 possible sites, 18 qualified (16 of which were qualified before the availability of SMAP data) as core validation sites for various spatial scales. Among the sites that did not qualify some sites were closer to qualifying than others. In some cases the issue was the data availability (latency) because the data are downloaded only annually and data records with sufficient lengths were not captured for establishing the validation metrics (Maqu is an example). Results from some sites may be somewhat inconclusive because the number of stations within the pixel was not large enough to qualify as a CVS; however, the pixel was characterized by exceptional homogeneity of land surface conditions (e.g., Kuwait). Based on these, and other stipulations there are potentially other sites that may qualify as CVS if additional studies involving modeling, analysis of precipitation patterns and establishment of scaling functions are conducted. Even though these actions were not completed by the time of this study, it is expected that more sites will meet the CVS requirements in the near future.

SMAP intended to produce soil moisture at three very different spatial resolutions and the CVS program was designed to support the validation of all three scales. Good examples of sites designed to support the validation at all three resolutions are TxSON and Yanco. Fig. 15 shows the TxSON and Yanco soil moisture station distribution within a 36-km grid pixel and highlights the 9-km and 3-km validation pixels. The SMAP extension of the Yanco site (Panciera et al., 2014) was designed and implemented well before the SMAP launch and had adopted the station locations to support the multiple scales based on the version 1 of the EASE grid. This was the grid of choice for the SMAP project at

Table 7
Validation of retrievals at 13 core validation sites performed over the 2.5-month period in 2015. R refers to Pearson correlation.

(m^3/m^3)	ubRMSE	bias	RMSE	R
Cropland				
St Josephs (0301)	0.051	−0.044	0.068	0.50
Kenaston (0301)	0.104	−0.025	0.107	0.40
Kenaston (0302)	0.087	−0.037	0.094	0.27
Monte Buey (0301)	0.080	−0.016	0.082	0.59
Valencia (0301)	0.032	0.026	0.041	0.42
Yanco YA4 (0301)	0.049	−0.020	0.053	0.83
Average	0.067	−0.019	0.074	0.50
RMS		0.030		
Grassland				
Walnut Gulch (0301)	0.014	0.024	0.028	−0.47[a]
TxSON (0301)	0.047	−0.038	0.060	0.8
TxSON (0302)	0.053	−0.029	0.060	0.72
Yanco YA7 (0302)	0.058	−0.013	0.059	0.75
Yanco YB5 (0303)	0.040	−0.017	0.069	0.81
Yanco YB7 (0304)	0.063	−0.008	0.063	0.52
Average	0.047	−0.019	0.057	0.52
RMS		0.024		
Shrublands				
Walnut Gulch(0302)	0.017	−0.013	0.022	0.08[a]
All site average	0.054	−0.016	0.062	0.47
All site RMS		0.026		

[a] At Walnut Gulch, the temporal variation in in situ soil moisture is very small, leading to the negative or no correlation.

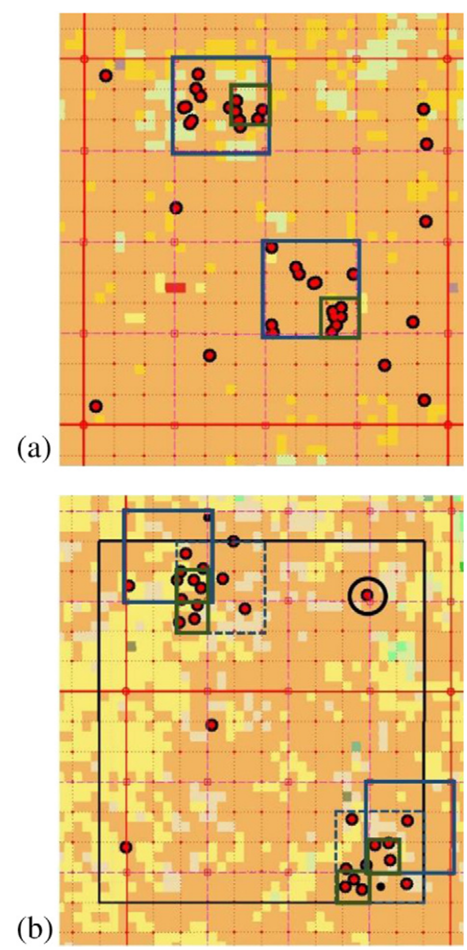

Fig. 15. (a) TxSON and (b) and Yanco. The images show the 36-km (red for TxSON and black for Yanco), 9-km (dark blue), and 3-km (dark green) pixels. For the Yanco 36-km pixel the validation grid processing is applied (the black outlines), and the dashed dark blue lines show the originally planned 9-km pixels which was based on EASE grid version 1. In (b) the circled station is the most representative station for the 36-km pixel. The marking of the grid lines is the same as in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

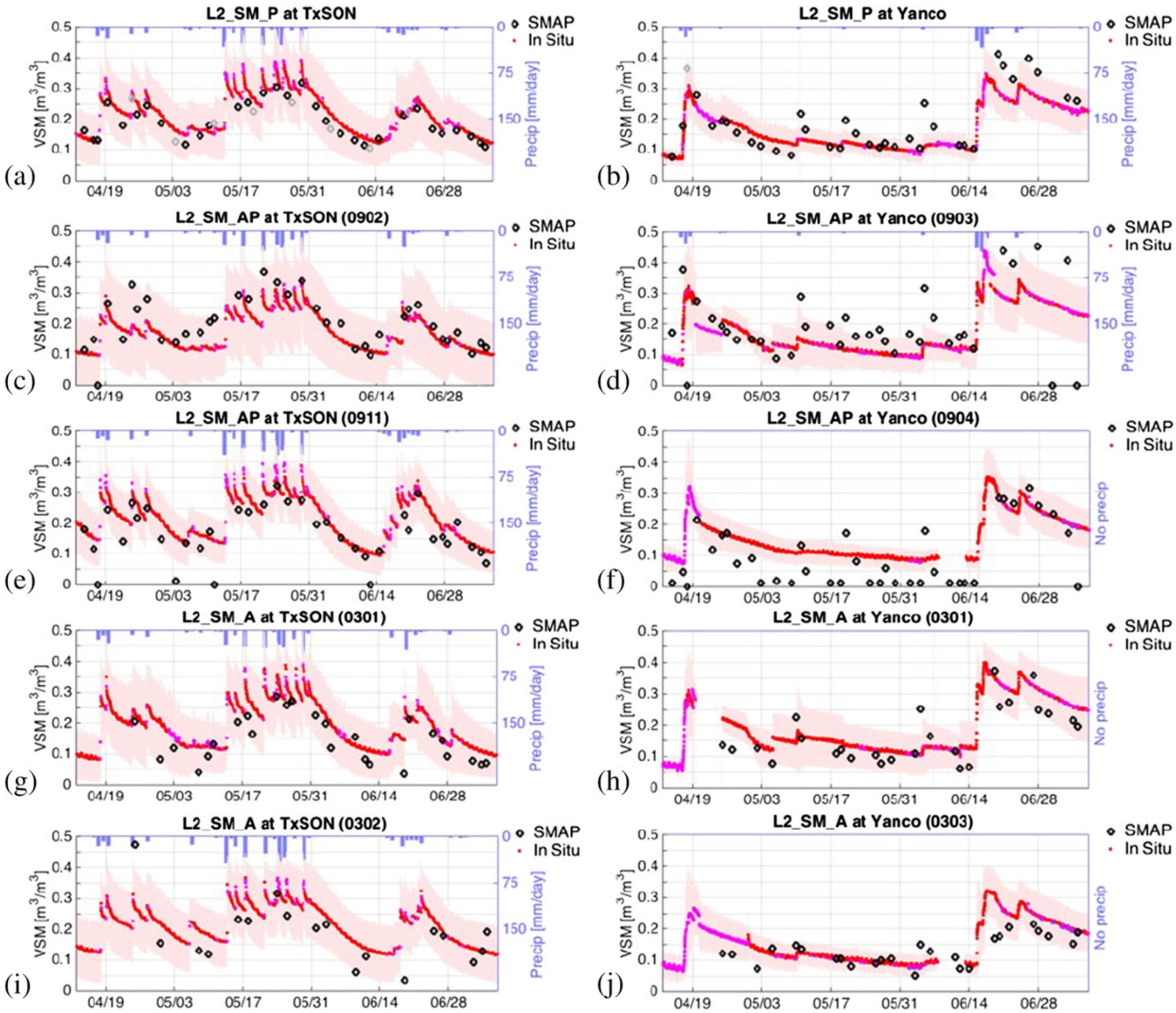

Fig. 16. Comparison of different spatial scales at TxSON (left-hand side) and Yanco (right-hand side) core validation sites. (a–b) show L2SMP and in situ average at 36-km scale; (b–f) show L2SMAP and in situ average over two pixels for each site at 9-km scale; (g–j) show L2SMA and in situ average over two pixels for each site at 3-km scale. See Fig. 10 caption for symbol definitions.

the time but was subsequently changed to version 2 upon its introduction. The validation grid processing overcame the mismatch between the site and grid for the 36-km product by aligning the validation grid pixel with the original design, but for the 9-km and 3-km products the standard grid was used. Fig. 15b shows the originally planned 9-km pixels with dashed lines. Fig. 16 shows the comparison of L2SMP, L2SMAP, and L2SMA with respective scale pixels. Over the TxSON and Yanco domains and during the time-frame of the SMAP radar operation the soil moisture evolution is relatively similar within each pixel based on the in situ measurements. Each product follows the in situ measurements demonstrating the overall functionality of the radiometer-based, radar-based and combined soil moisture retrievals.

In Yee et al. (2016) the representative stations (see Section 5.1) were determined for the Yanco reference pixels. Fig. 17 shows the time-series

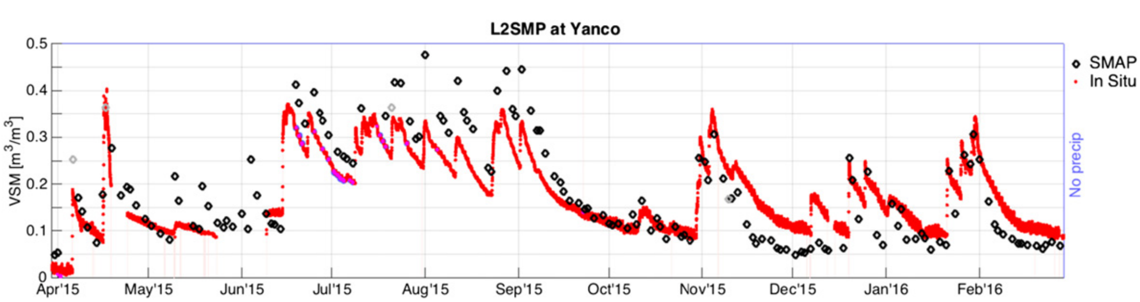

Fig. 17. Comparison of the most representative station of the Yanco 36-km pixel to the SMAP L2SMP soil moisture product.

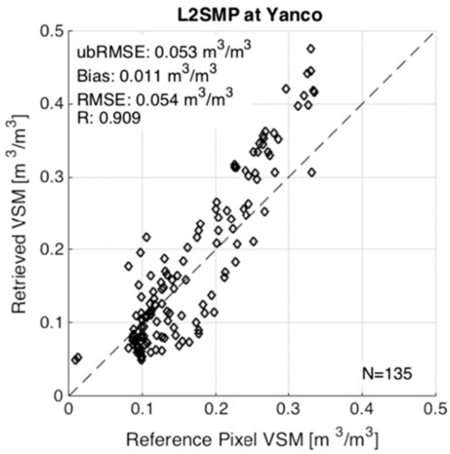

Fig. 18. Scatterplot between the most representative station of the Yanco 36-km pixel and the SMAP L2SMP soil moisture product.

for the most representative station in the pixel (the station is circled in Fig. 15) and the L2SMP product soil moisture in the 36-km pixel, and Fig. 18 shows the respective scatterplot. A comparison to results presented in Section 6.1 indicates that the correspondence is better when using the weighted average of all stations within the pixel. The difference is largest in RMSE while the bias is in fact slightly smaller when using the most representative station. The correlation obtained using the most representative station is also close to the one obtained with the average. This suggests, as expected, that the average-based soil moisture captures better the soil moisture over a range of conditions (different drying and wetting patterns; seasonal variations, etc.) while the most representative station manages to reflect the wetting and drying trends and the overall soil moisture condition in the pixel.

8. Conclusions

SMAP has produced 36-km radiometer-based soil moisture data product (L2SMP), 3-km radar-based soil moisture product (L2SMA), and 9-km radiometer-radar combined product (L2SMAP). However, the radar ceased operation prematurely in July 2015, which limited the length of the time-series of the products that required radar data. The SMAP mission implemented a comprehensive Cal/Val program for the validation of its geophysical data products. The approach is founded on the utilization of a global network of core validation sites (CVS) that provides reliable estimates of soil moisture at SMAP grid product scales. Out of the 34 candidate sites 18 fulfilled all the requirements at one of the resolution scales (at least), while the rest provide useful supporting observations. Many are also expected to qualify to achieve CVS status in the near future, which will also further diversify the land surface conditions represented by the CVS. The data from the sites are quality controlled before application of site specific spatial scaling function and comparison with the SMAP soil moisture products. The results presented in this paper demonstrate that the SMAP Cal/Val program was implemented successfully and has been used for timely and precise validation of the SMAP soil moisture products. Furthermore, the comparisons show that the performance of the SMAP soil moisture data products is within mission requirements. The SMAP radiometer-based soil moisture data product meets its expected retrieval accuracy of 0.04 m^3/m^3 volumetric soil moisture (ubRMSD); the combined radar-radiometer product is close to its expected performance of 0.04 m^3/m^3, and the radar-based product meets its target accuracy of 0.06 m^3/m^3. The effort to compare SMAP soil moisture products, in particular the radiometer-based product, will continue beyond the intensive Cal/Val phase in order to monitor and improve the performance of the products.

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