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Satellite surface soil moisture from SMOS and Aquarius: Assessment for applications in agricultural landscapes

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ABSTRACT

Satellite surface soil moisture has become more widely available in the past five years, with several missions designed specifically for soil moisture measurement now available, including the Soil Moisture and Ocean Salinity (SMOS) mission and the Soil Moisture Active/Passive (SMAP) mission. With a wealth of data now available, the challenge is to understand the skill and limitations of the data so they can be used routinely to support monitoring applications and to better understand environmental change. This paper examined two satellite surface soil moisture data sets from the SMOS and Aquarius missions against in situ networks in largely agricultural regions of Canada. The data from both sensors was compared to ground measurements on both an absolute and relative basis. Overall, the root mean squared errors for SMOS were less than 0.10 $m^3\,m^{-3}$ at most sites, and less where the in situ soil moisture was measured at multiple sites within the radiometer footprint (sites in Saskatchewan, Manitoba and Ontario). At many sites, SMOS overestimates soil moisture shortly after rainfall events compared to the in situ data; however this was not consistent for each site and each time period. SMOS was found to underestimate drying events compared to the in situ data, however this observation was not consistent from site to site. The Aquarius soil moisture data showed higher root mean squared errors in areas where there were more frequent wetting and drying cycles. Overall, both data sets, and SMOS in particular, showed a stable and consistent pattern of capturing surface soil moisture over time.

1. Introduction

Remotely sensed observations of surface soil moisture are becoming increasingly available from a number of satellite missions, including those with soil moisture as their dedicated purpose, such as the Soil Moisture and Ocean Salinity mission (SMOS; (Kerr et al., 2012)) and the Soil Moisture Active/Passive mission (SMAP; (Entekhabi et al., 2010)). Other missions such as the Aquarius mission (Bindlish et al., 2015), Advanced Microwave Scanning Radiometer (AMSR-E/AMSR-2; (Imaoka et al., 2010; Njoku et al., 2003)) missions, and ASCAT /METOP-A (Naeimi et al., 2009; Wagner et al., 1999) all have or had soil moisture data sets that are available widely for research and applications use. This wealth of soil moisture information holds great potential for advancing the understanding of soil moisture and related biogeochemical cycles that have implications for a diverse array of applications, such as improving weather and climate prediction, hydrological flood forecasting and climate-related risk assessment. The challenge in making use of these data sets is in understanding the strengths and limitations of each data set, where it is capturing relative trends and where it is not. This research will compare surface satellite soil moisture from the SMOS mission and the now completed Aquarius mission, two L-band passive microwave sensors, to field-measured values, and assess the ability of the data sets to capture relative and relevant trends in moisture availability over a multi-year period.

A variety of modelling approaches, assumptions and methods of estimating ancillary variables are used to retrieve soil moisture information from active and passive microwave sensors, which leads to differences in estimated soil moisture that are over and above those resulting from differences in the electromagnetic fre-

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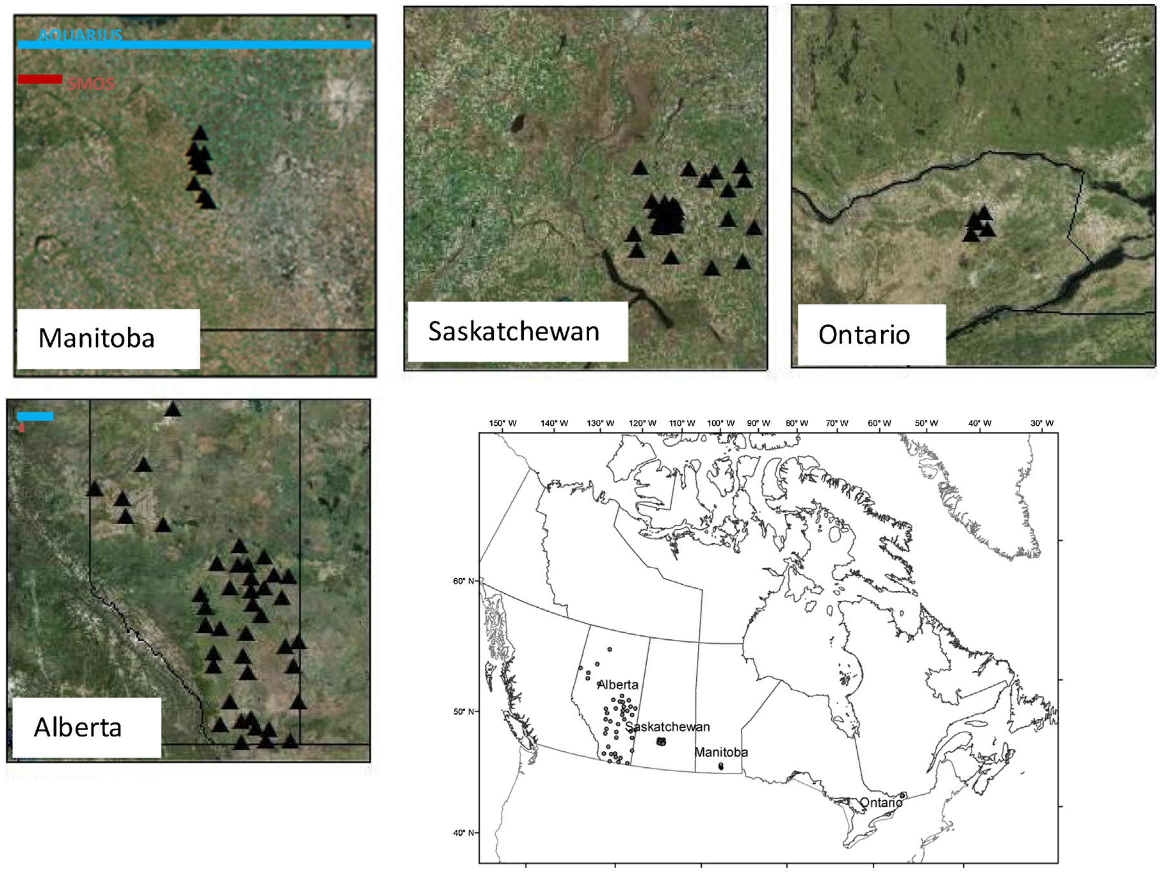

Fig. 1. Location scale of in situ soil moisture monitoring sites in agricultural regions of Canada. Comparison of SMOS (red bar) and Aquarius (blue bar) spatial scale (top left corner) compared to in situ monitoring locations (black triangles) for the selected networks in this study. Manitoba, Saskatchewan and Ontario networks shown at the same scale; Alberta mesonet shown at larger scale to capture full extent of network. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Error Statistics for SMOS and Aquarius surface soil moisture compared to in situ measurements at network locations.

Site	SMOS			Aquarius		
	aRMSE	cRMSE	*R*	aRMSE	cRMSE	*R*
Ontario	0.07	0.08	0.80	0.17	0.05	0.63
Manitoba	0.11	0.12	0.51	0.12	0.12	0.70
Saskatchewan	0.05	0.05	0.75	0.09	0.08	0.79
Alberta (average)	0.10	0.10	0.60	0.15	0.09	0.47

quency and engineering used to collect the radiometric information (Owe et al., 2000). Passive microwave sensors such as SMOS, SMAP and Aquarius measure brightness temperature, which is impacted by differences in surface soil moisture, but is also based on factors such as surface temperature, vegetation water content and surface roughness and/or topography. Most radiative transfer models that are used to estimate surface soil moisture from passive microwave satellites are developed over bare to low biomass vegetative surfaces. The uncertainty in land cover data sets, which leads to uncertainty in the distribution of different contributing areas within the sensor footprint, results in uncertainty in the estimation of the contribution of each land cover to the brightness temperature measurements. Additionally, models to retrieve soil moisture over forested regions are less robust, leading to further uncertainty. The strategies used to estimate these ancillary variables such as land cover and vegetation water content can lead to different estimates of surface soil moisture from different satellites and different retrieval methods.

Numerous studies have looked at the validation of SMOS soil moisture data since the launch of the sensor in 2009. Several studies found that SMOS soil moisture tends to underestimate soil moisture or exhibits a dry bias, particularly in arid areas, when compared to local measurements (Al Bitar et al., 2012; Dall'Amico et al., 2012; Djamai et al., 2015; Jackson et al., 2012; Lacava et al., 2012; Sanchez et al., 2012). The SMOS soil moisture retrieval algorithm tends to overestimate the moisture relative to ground measurements following large rainfall events, a fact that has been attributed to physical differences in the sensing depth of the sensor versus the in situ measurements (Jackson et al., 2012). SMOS soil moisture has been shown to be more sensitive to moisture at the very surface (0–5 cm) than to soil moisture measured horizontally at a 5 cm depth (Adams et al., 2015). Overall, root mean squared errors (RMSE) between SMOS soil moisture and in situ have been reported between 0.02 $m^3 m^{-3}$ and 0.10 $m^3 m^{-3}$, with differences often higher where significant forest, wetland or open water is present in the foot print of the SMOS pixel (Al Bitar et al., 2012). The temporal correlation of SMOS with the in situ soil moisture time series in the above-mentioned studies varies considerably depending on the geography and climatology of the sites that are examined, the number of in situ monitoring sites present within the radiometer footprint, the time period over which the data are assessed and other factors such as Radio Frequency Interference (RFI). Several researchers have looked at the accuracy of SMOS over sites in Canada during intensive field campaigns, including the Can-Ex field campaign over a 12 day period in 2010 (Gherboudj et al., 2012; Magagi et al., 2013) and the 42 day SMAPVEX-12 experiment in 2012 (Adams et al., 2015; McNairn et al., 2015). Over a two month

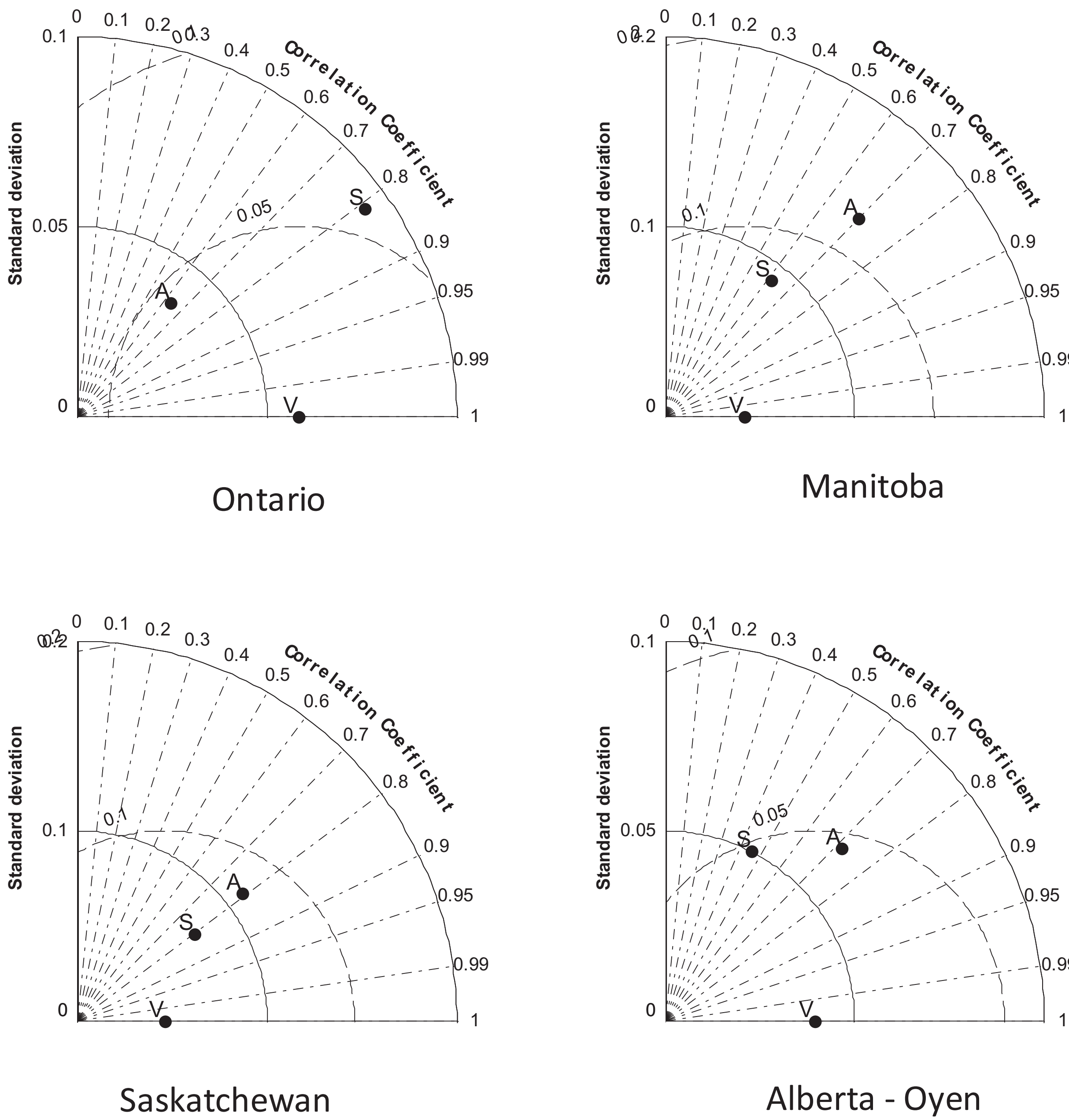

Fig. 2. Taylor Diagrams showing accuracy of SMOS (S) and Aquarius (A) soil moisture as compared to the in situ measurement at 5 cm depth (V). These diagrams show the relative position of the soil moisture data to the reference data set using linear correlation coefficient, centered root mean squared error and the standard deviation.

period in 2010, an RMSE of 0.15–0.18 $m^3\,m^{-3}$ was found between in situ networks in Saskatchewan, with the RMSE between satellite and in situ observations increasing with increased soil wetness (Gherboudj et al., 2012). There were some limitations to this analysis, since the validation occurred over a period of unusual wetness and the soil moisture for this region and was above 0.30 $m^3\,m^{-3}$ for the duration of the campaign. An examination over a longer period using the more recent version of the SMOS soil moisture retrieval algorithm at the same site showed a reduced RMSE at this site, ranging from 0.06 to 0.12 $m^3\,m^{-3}$ (Djamai et al., 2015). An examination of SMOS soil moisture over the in situ network near Elm Creek, Manitoba over a two year period showed RMSE values of 0.10–0.12 $m^3\,m^{-3}$ between in situ and satellite observations, with relatively low temporal correlation of 0.22–0.64 (Adams et al., 2015). Aquarius soil moisture has had more limited validation, due to its short mission duration, but results over sites in agricultural regions in the United States found an RMSE of 0.03 $m^3\,m^{-3}$, a dry bias of 0.01 $m^3\,m^{-3}$ and a correlation of 0.85 (Bindlish et al., 2015).

One of the limitations of some of these studies was that validation was performed over a relatively short time period, using earlier versions of the satellite data. Some of the issues leading to reduced accuracy have been improved with subsequent reprocessing of the data. In addition, validation results have been shown to change as more data is incorporated into the validation period, and the validation statistics stabilize (Jackson et al., 2012). Moreover, for many applied uses of soil moisture data, the use of accuracy statistics on absolute volumetric soil moisture can sometimes be misleading, particularly for applications that require data on relative trends rather than absolute values. Relative trends are important for if conditions are wetter or drier than normal, and this can support applications ranging from drought and excess moisture

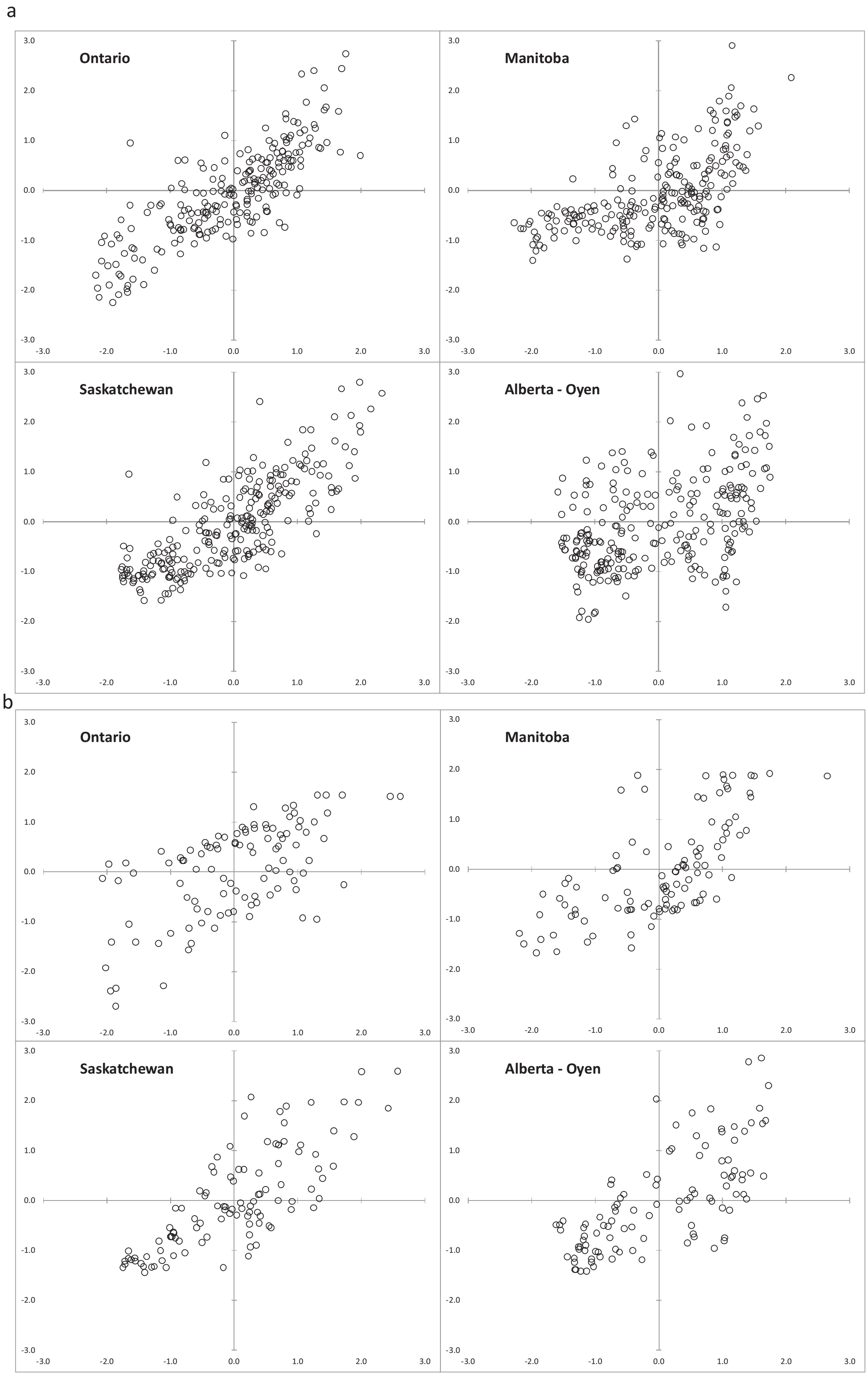

Fig. 3. (a) Comparison of in situ and SMOS derived surface soil moisture (expressed as deviation from average value) for three validation network locations and one selected mesonet site in Alberta. (b) Comparison of in situ and Aquarius derived surface soil moisture (expressed as deviation from average value) for three validation network locations and one selected mesonet site in Alberta.

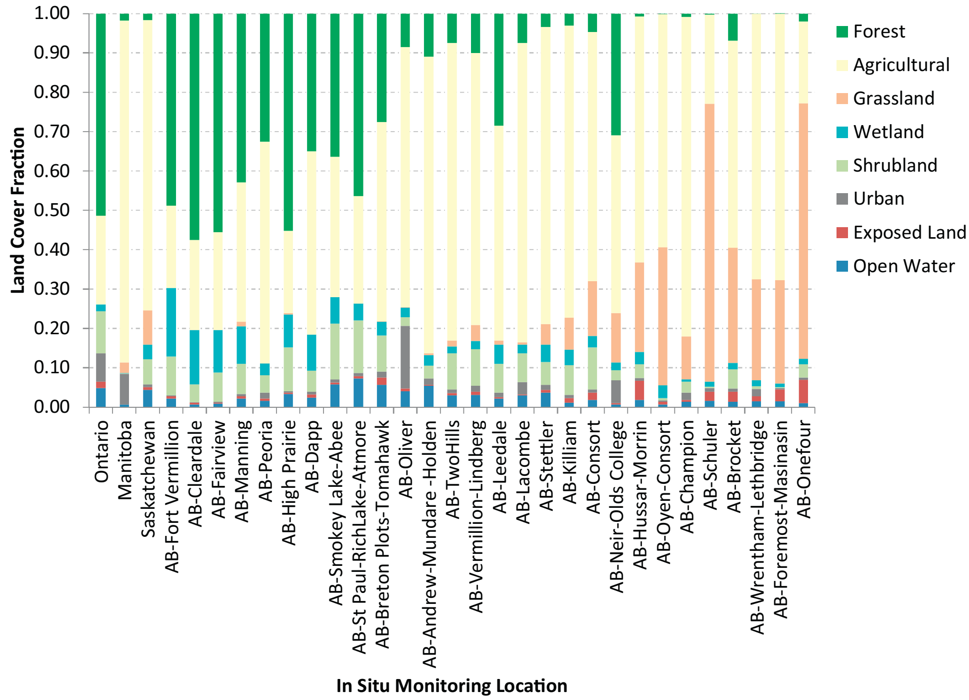

Fig. 4. Land cover fractions within each pixel (based on Aquarius pixel footprint). The SMOS fractions are not shown but in most cases are similar.

monitoring, to soil trafficability, to data assimilation (Albergel et al., 2013; Champagne et al., 2015; Loew et al., 2009).

The purpose of this research is to provide an examination SMOS and Aquarius soil moisture data over an extended validation period compared to in situ measurements, as well as determine on a relative basis when and where each data set is useful in estimating soil moisture trends in the environment. The validation was done through a comparison with in situ measured soil moisture at numerous sites distributed over agricultural regions in Canada. In situ measurements and satellite based observations differ in the physics and scale of what they measure, and as a result the interpretation of the error statistics used to compare them should take this into account.

Table 2
Error Statistics for SMOS and Aquarius surface soil moisture compared to in situ measurements for all stations in the Alberta mesonet.

Site	SMOS			Aquarius		
	aRMSE	cRMSE	*R*	aRMSE	cRMSE	*R*
Cleardale	n/a	n/a	n/a	0.07	0.12	0.34
Fairview–Peoria	0.11	0.05	0.70	0.21	0.13	0.26
Manning	0.17	0.05	0.58	0.11	0.09	0.45
Tomahawk	0.13	0.06	0.58	0.16	0.16	0.12
Leedale–Breton Plots	0.21	0.05	0.55	0.25	0.16	0.13
Neir	0.07	0.05	0.68	0.20	0.17	0.06
Dapp	0.09	0.05	0.26	0.06	0.09	0.32
Brocket	0.12	0.07	0.60	0.07	0.11	0.57
Lacombe–Olds College	0.10	0.06	0.61	0.08	0.07	0.70
Oliver	0.09	0.06	0.53	0.06	0.08	0.59
Del Bonita	0.06	0.04	0.74	0.05	0.06	0.67
Champion	0.06	0.05	0.70	0.09	0.05	0.73
Morrin–Stettler	0.09	0.05	0.63	0.09	0.07	0.69
Hussar	0.12	0.06	0.62	0.07	0.08	0.61
Andrew–Mundare–TwoHills	0.10	0.07	0.57	0.13	0.06	0.76
Barnwell–Lethbridge	0.07	0.04	0.70	0.02	0.04	0.74
Wrentham	0.07	0.05	0.76	0.05	0.05	0.77
Killiam	0.09	0.05	0.58	0.06	0.08	0.60
Foremost	0.09	0.04	0.82	0.13	0.07	0.46
Onefour	0.08	n/a	n/a	0.05	0.12	-0.09
Oyen	0.11	0.05	0.46	0.06	0.05	0.71
Bodo	0.09	n/a	n/a	0.08	0.07	0.63
Schuler	0.13	0.05	0.57	n/a	0.04	0.70

2. Methodology

2.1. Study sites and ground data measurements

Four in situ networks were used to evaluate the SMOS and Aquarius soil moisture data sets over Canada (Fig.1). Two networks (Manitoba and Ontario) are run by Agriculture and Agri-Food Canada as part of Real Time In Situ Monitoring for Agriculture (RISMA), one is run by the University of Guelph and Environment Canada (Saskatchewan) and one run by Alberta Agriculture and Rural Development. All of the networks are located in largely agricultural regions, although the percentage of agricultural land, the cultivation practices, the soil and landscape types and the climate vary between (and sometimes within) the sites. Three of these networks (Ontario, Manitoba and Saskatchewan) consist of multiple stations covering a relatively small area to capture soil moisture variation within the radiometer for validating modelled and satellite observed soil moisture data. The fourth network in Alberta is a mesonet that captures soil moisture variability over a province, with only one or two soil moisture stations representing the soil moisture variability within the radiometer footprint.

More details on these networks can be found elsewhere (Adams et al., 2015; Champagne et al., 2010; Walker and Howard 2003), so only a brief description is given here: (1) The network near Kenaston, Saskatchewan (SK) consists of two sub networks: a dense grid of 22 stations over a 10 by 10 km area and a more spatially dispersed network consisting of 14 stations covering an area of approximately 60 by 60 km. Each station consists of horizontally buried dielectric probes (Stevens Hydra Probe SDI-12) at 5 cm, 20 cm and 50 cm. The 22 stations within the smaller grid also have a vertically orientated probe measuring 0–5 cm. This network is located in the Brightwater Creek watershed, and consists of a Prairie/grassland ecosystem cultivated with small grain cereal and oilseed crops and interspersed with both native and managed grassland areas. The average

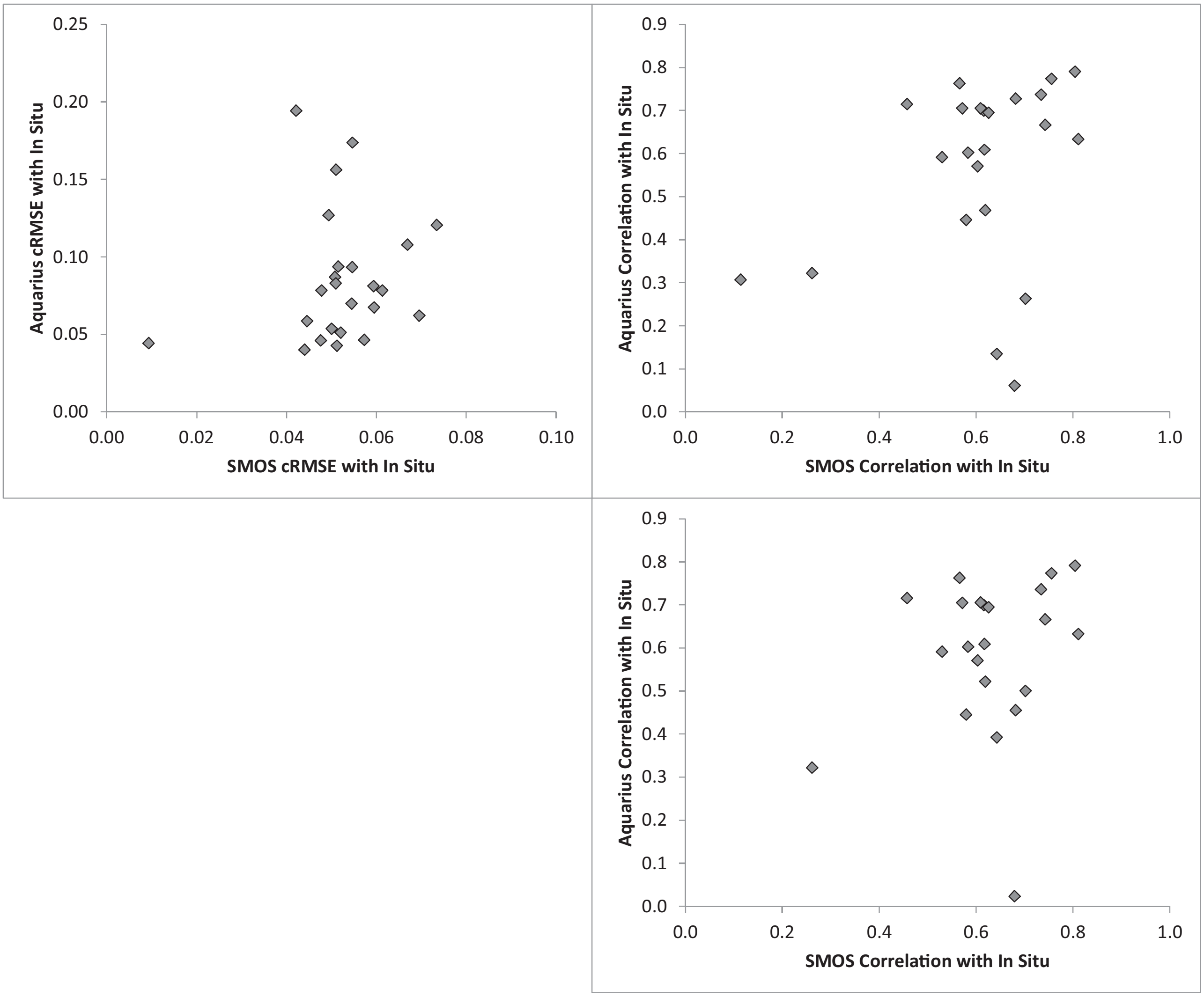

Fig. 5. Relationship between SMOS and Aquarius RMSE and *R* with in situ data for all study sites. Top left: relationship between SMOS and Aquarius centred Root Mean Squared Error (cRMSE); top right: relationship between SMOS and Aquarius linear correlation coefficient (*R*); bottom right: relationship between SMOS and Aquarius correlation coefficient when data have been screened for high data values.

temperature during the growing season is 11 °C and on average 278 mm of precipitation (primarily rain) during April–October period. (2) The network near Elm Creek, Manitoba (MB) consists of 9 stations distributed over a largely agricultural region in the Prairie/Boreal Plain Ecozone in the Red River watershed and is part of the RISMA network. Each station consists of three sets of replicate dielectric probes (Stevens Hydra Probe SDI-12) installed vertically at 0–5 cm, and horizontally at 5 cm, 20 cm, 50 cm and 100 cm. These are calibrated to derive soil moisture using a site and depth specific methodology (Ojo et al., 2015). The network covers two predominant soil types: heavy Red River clay soils to the north–east and sandier loam soils to the south–west. The land use is largely cultivated annual crop land of cereals, oilseeds, legumes, corn and managed pasture. Average temperature during the growing season is 13 °C with average precipitation (primarily rain) of 397 mm from April to October. (3) The network near Casselman, Ontario (ON) consists of 5 stations over an area of approximately 20 by 20 km that is largely agricultural but bordered by patches of forest and two large rivers and is also part of the RISMA network. Like the MB network, each station consists of three sets of replicate dielectric probes (Stevens Hydra Probe SDI-12) installed vertically at 0–5 cm, and horizontally at 5 cm, 20 cm and 50 cm, with one station measuring moisture values at 100 cm, based on the depth to the water table. The area consists primarily of cultivated corn, soybean with smaller production of forage and small grains. The average temperature from April to October is 14 °C with 583 mm of precipitation (largely rainfall) during this time. (4) The Alberta Drought Monitoring Network (AGDMN) is a mesonet that covers the agricultural regions of the province of Alberta, stretching from 56°N in the north to 49°N in the south. Stations were sited to capture moisture variability at the provincial scale, with 38 stations measuring soil moisture. Each station consists of dielectric probes (Delta-T Theta) buried horizontally at 5 cm 20 cm, 50 cm and 100 cm. The landscape varies considerably over the mesonet, with the northern stations in the Peace River region amid the Boreal plain, with mixed Prairie grasslands in the southeast, boreal transition zones in the central areas and lee areas of the Montane Cordillera to the west. Temperatures and rainfall vary, with a general dry continental climate. The average April to October temperatures of 10 °C in the High Prairie to the north 12.5 °C in Lethbridge in the south and precipitation ranging from 300 mm in the High Prairie area in the north to 250 mm in drier regions of the southeast such as Oyen in the east of the province.

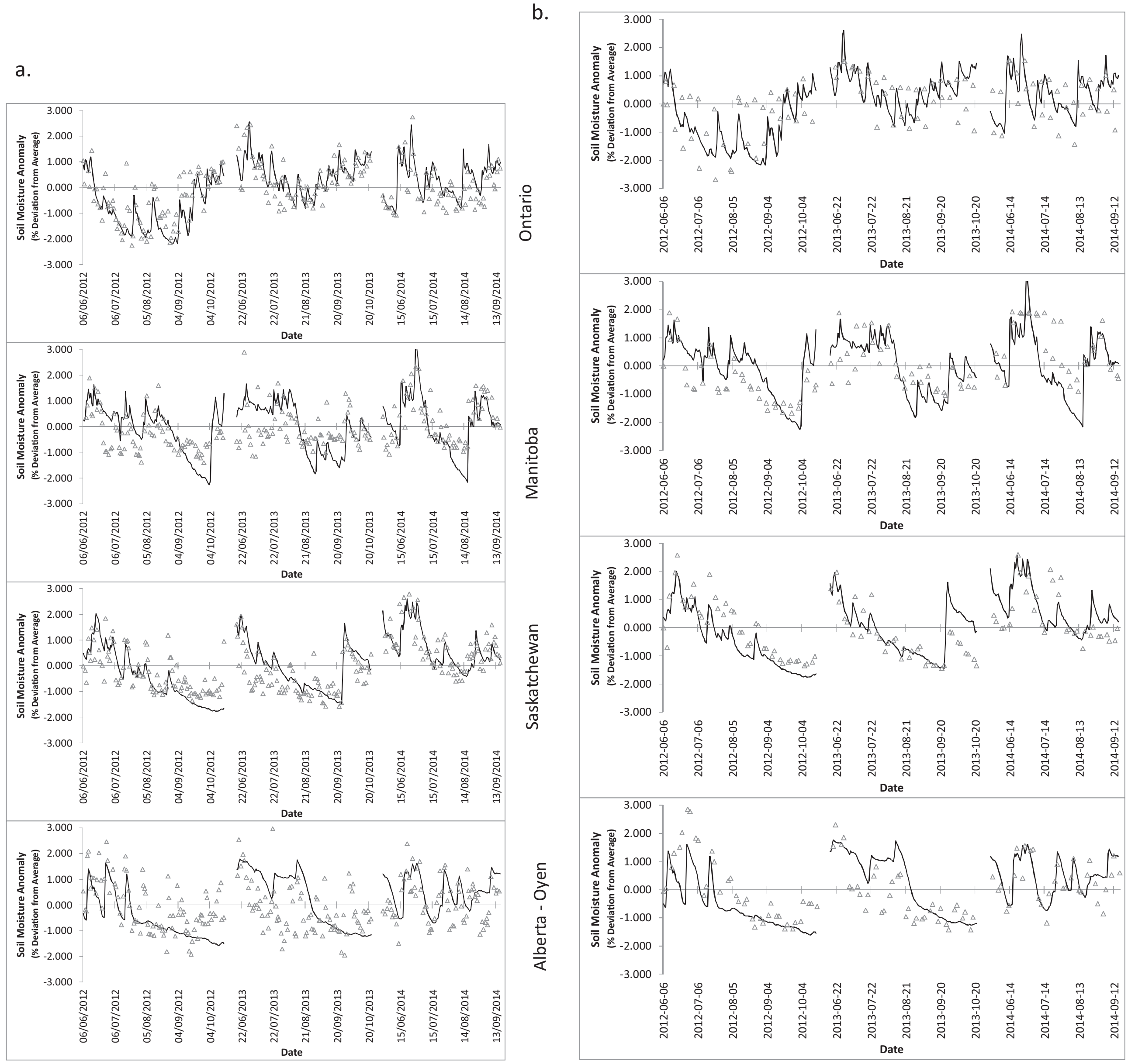

Fig. 6. (a) Time series of in situ and SMOS surface soil moisture for 3 year evaluation period. The soil moisture is expressed as the standard deviation from the long term average. (b) Time series of in situ and Aquarius surface soil moisture for 3 year evaluation period. The soil moisture is expressed as the standard deviation from the long term average.

The SK and MB networks have been used in the past for validating coarse resolution satellite remote sensing, and have shown good agreement with area averaged, field collected soil moisture at the surface (Adams et al., 2014). At all sites, sensors were calibrated to absolute volumetric soil moisture using the best available site specific calibration procedures to estimate soil moisture within +/−2% accuracy (Burns et al., 2014; Walker and Tajek, 2006).

For each station, the surface soil moisture probe buried horizontally at a depth of 5 cm was used for validation of the satellite soil moisture products. This was done to be consistent with a measurement that was available at all sites, since not all sites had vertically installed probes. A previous examination of the differences between the vertical and horizontal probes was made at the Manitoba site, and found the vertical probes to give lower soil moisture values than those installed horizontally (Adams et al., 2015). Satellites measuring microwave radiation at L-band are sensitive to soil moisture at the surface, which in some cases may be less than 5 cm. The depth of soil that contributes to the radiometer observation becomes shallow when the near surface is wet. This may occur during and shortly after a precipitation event. After some elapsed time, the soil moisture profile will become more uniform (i.e. the moisture level at the surface will be roughly consistent over the 0–5 cm profile of the soil) (Escorihuela et al., 2010; Jackson et al., 2012). This difference in sensing depth should be understood by users; after large rainfall events, the SMOS measurement may represent a thinner contributing layer. For this study, we did not flag out measurements that occurred shortly after rainfall events, since this information is often most valuable to users. Instead, it should be noted that this would be a source of difference between in situ and satellite data in the validation statistics. For all sites, the soil moisture measured on the ground was averaged for all sites within the radiometer footprint to compare with the corresponding satellite value.

2.2. Satellite soil moisture data

Satellite soil moisture data were obtained from the European Space Agency (SMOS) and NASA (Aquarius). Both data sets were processed to volumetric surface soil moisture using the operational soil moisture retrieval algorithm in use at the time of publication. For both sensors, soil moisture was evaluated within the May to October time period, which corresponds with the period where most land areas are snow-free over these study sites and where ground data were consistently available from all networks. Surface temperature from the data sets was examined to determine if soils were frozen during these acquisition periods, and these were excluded from the assessment if the soil temperature was below 3 °C. The SMOS data used was from the Level 5.51 version of the soil moisture processor, with data reprocessed using this processor for 2010–2014. The SMOS soil moisture processor uses the tau-omega model to quantify soil dielectric constant and vegetation opacity using multi-angular brightness temperature and an iterative optimization method to achieve a best fit between measured and modelled brightness temperatures (Kerr et al., 2012). Auxiliary information on surface temperature is obtained from European Centre for Medium Range Weather Forecasts (ECMWF). SMOS soil moisture from ascending and descending passes was extracted for the Discrete Global Grid (DGG) location nearest to each in situ monitoring station for the evaluation. Aquarius daily gridded soil moisture (Level 3, Version 3 of the data) is derived using the Single Channel Retrieval (SCA) model to estimate soil dielectric constant from horizontal polarized brightness temperatures (Bindlish and Jackson 2013; Jackson 1993). Surface temperature is obtained from National Centers for Environmental Prediction's Global Forecast System (NCEP GFS) and vegetation water content is estimated using Normalized Difference Vegetation Index (NDVI) from the MODIS sensor. SMOS soil moisture data has a footprint of approximately 40 km, but is gridded to a 15 km global grid, with moisture values representing conditions surrounding each node, whereas Aquarius soil moisture represents a contributing area of up to 156 km depending on the beam, and is obtained at a resolution of 1° (approximately 70–80 km at these latitudes). The SMOS data were examined for both the ascending and descending passes, which occur at 6:00 and 18:00 local time, respectively. The results from both passes were similar, so reference is only made to the results from the ascending pass. For Aquarius, the daily composites used spectral information from both ascending and descending passes using information from three beams with different incidence angles (Bindlish et al., 2015). A key distinction between SMOS and Aquarius soil moisture data is the temporal revisit frequency. SMOS soil moisture is available at these latitudes on average every 1.5 days, whereas Aquarius is available at these latitudes on average every 3.5 days, which limits its sensitivity to long term wetting and drying events (Bindlish et al., 2015).

SMOS and Aquarius surface soil moisture has been shown to have a dry bias through previous validation efforts, as was discussed in the introduction. To assess the ability of SMOS and Aquarius to capture relative trends rather than absolute soil moisture, soil moisture anomalies were calculated for each data set according to a method described by (Champagne et al., 2010; Crow et al., 2005). To calculate anomalies, the average and standard deviation were calculated from the full data record of both satellite and in situ measurements and the observed anomaly was calculated as the measured value less the average, normalized by the standard deviation. This normalization results in data sets for each satellite and the ground measurements with an average of zero and a standard deviation of one, and the units become normal deviates around the mean value. This method accounts for systematic differences in climatology between data sets that occur because of differences in the volume of soil that each data set represents, as well as radiometric differences in the measured brightness temperature resulting from sensor calibration on the satellites. The absolute root mean squared error (aRMSE), the centered root mean squared error (cRMSE) and linear correlation coefficient (R) were calculated for the evaluation. The cRMSE differs from the aRMSE are calculated as:

$$\mathrm{aRMSE} = \frac{1}{n}\sqrt{\sum\nolimits_{n=1}^{N}(\mathrm{SM}_{\mathrm{InSitu}} - \mathrm{SM}_{\mathrm{Satellite}})^2} \quad (1)$$

$$\mathrm{cRMSE} = \frac{1}{n}\sqrt{\sum\nolimits_{n}^{N}[(\mathrm{SM}_{\mathrm{InSitu}} - \mathrm{SM}_{\mathrm{MeanInSitu}}) - (\mathrm{SM}_{\mathrm{Satellite}} - \mathrm{SM}_{\mathrm{MeanSatellite}})]^2} \quad (2)$$

where $\mathrm{SM}_{\mathrm{Observed}}$ is the soil moisture measured by the in situ station, $\mathrm{SM}_{\mathrm{Satellite}}$ is the soil moisture measured by the satellite, and $\mathrm{SM}_{\mathrm{Mean}}$ is the average value over all of the observed and satellite values, and n is the number of observations. The cRMSE centers the aRMSE by removing some of the bias from the measured soil moisture values such that the differences in the patterns of the two data sets can be isolated from the differences in the means of the two data sets. This enables a Taylor diagram comparison to evaluate the performance of the satellite soil moisture data sets against the in situ networks, in combination with the correlation coefficient (Taylor, 2001). Due to diurnal differences in the acquisition times between Aquarius and SMOS, direct comparison was not made between the two satellite soil moisture data sets. Instead both data sets were compared directly to the in situ measurements made coincident to the satellite acquisition. To enable comparison between data sets of different sizes, the analysis was restricted to periods where both Aquarius and SMOS data were available coincident to in situ measurement periods. Since the Aquarius overpasses were less frequent than the SMOS overpasses, the SMOS data set was subsampled to create a data set of equal size for each validation site. The SMOS data record was subsampled randomly using 100 iterations of sub-samples to create evaluation subsets, and statistics were calculated on each subset. The average statistics over these iterations are reported.

3. Results and discussion

3.1. Comparison of SMOS and Aquarius soil moisture with in situ networks

Taylor diagrams comparing in situ soil moisture with SMOS (S) and Aquarius (A) soil moisture are shown in Fig. 2 for the Ontario, Manitoba, Saskatchewan and a selected site for Alberta. Taylor diagrams compare the correlation coefficient (R), the centered root mean squared error (cRMSE) and the standard deviation of modelled data sets to an observed value to show how far modelled data sets lie in this three dimensional space from the observed soil moisture value. The closer a point is to the in situ measured value, the closer the satellite data is to the ground measured data. The diagrams show that the SMOS soil moisture is closer to the in situ for the Saskatchewan and Manitoba sites than Aquarius, with Aquarius and SMOS comparing more or less equivalently for the Ontario and the selected site in Alberta.

For the Ontario site, the SMOS data showed a higher correlation with in situ but a slightly lower cRMSE than Aquarius, with cRMSE values of 0.08 $m^3\,m^{-3}$ for SMOS and 0.05 $m^3\,m^{-3}$ for Aquarius (Table 1). The standard deviation of the soil moisture was closer to that of the reference data set for Aquarius at this site than it was for SMOS. This suggests that the SMOS data is capturing the relative trend of the data better than Aquarius, but that the absolute RMSE in SMOS soil moisture is higher compared to what is captured by the in situ sensors. For the Manitoba site, the cRMSE

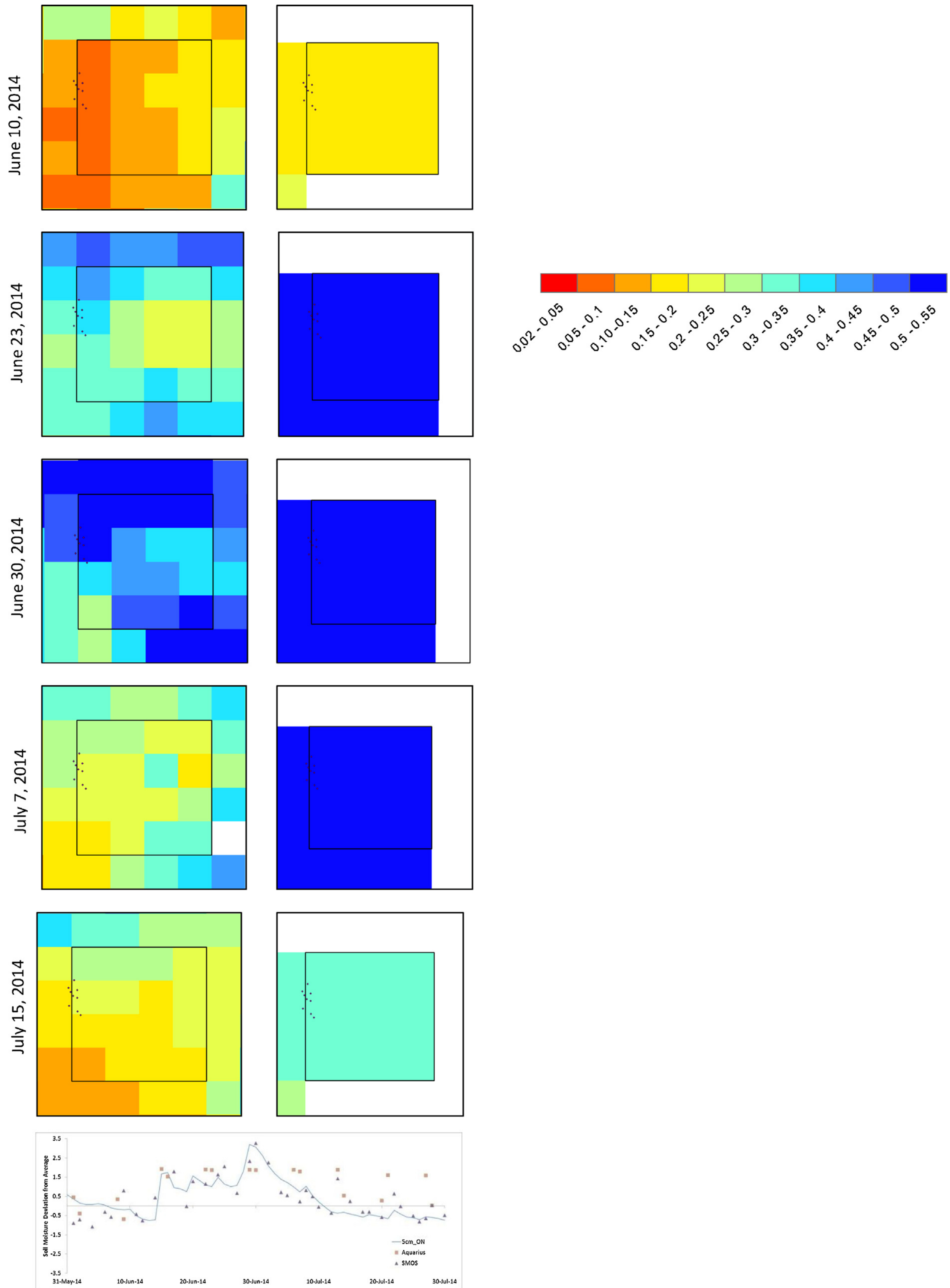

Fig. 7. Time series showing SMOS (left) and Aquarius (right) values during a heavy rainfall event in June–July 2014 for the Manitoba site. Bottom graph shows extracted values for the relevant pixel where in situ stations are located for surface soil moisture. Dots show locations of in situ soil moisture measurement stations relative to the Aquarius pixel (black square).

was higher for Aquarius than for SMOS (0.12 $m^3 m^{-3}$ for Aquarius versus 0.07 $m^3 m^{-3}$ for SMOS), with the SMOS having a lower correlation at this site. In Saskatchewan, Aquarius had a higher RMSE than SMOS (0.12 and 0.05 $m^3 m^{-3}$, respectively), with comparable correlation coefficients. Looking at the Alberta sites overall, the correlation was much lower with both sensors (0.62 for SMOS and 0.47 for Aquarius), but cRMSE was comparable to the other sites. For the numerous sites in Alberta, there was, not surprisingly, great variability in the relationship between in situ and satellite soil moisture from site to site. This is likely due to the fact that each pixel only had one or two sites within the radiometer footprint measuring soil moisture, and these sites were not necessarily selected to capture soil moisture at a coarser scale. The variation in R and cRMSE was substantial, with R values as low as 0.26 for SMOS and negative correlations for Aquarius, and as high as 0.76 for SMOS and 0.77 for Aquarius, with a standard deviation of 0.11 around an average of 0.62 for SMOS; 0.31 around an average of 0.47 for Aquarius (Table 2).

The average SMOS soil moisture was in general much lower than for Aquarius, and compared to the in situ data set, showed a consistent dry bias as seen with other sites and other studies. The cRMSEs in soil moisture retrieval for the AB sites averaged 0.10 $m^3 m^{-3}$ for SMOS and 0.09 $m^3 m^{-3}$ for Aquarius. The range for cRMSE was 0.01 $m^3 m^{-3}$ for SMOS and 0.04 $m^3 m^{-3}$ for Aquarius. The results for the MB site are consistent with what has been reported previously for SMOS at this site (Adams et al., 2015), indicating that these statistics are relatively stable in time. The results are also somewhat improved over previous evaluations conducted at the site in Kenaston, SK using this version of the SMOS soil moisture processor (Djamai et al., 2015), with the a slightly lower RMSE and a slightly higher correlation, likely due to the longer time period of this assessment. The RMSE between Aquarius and in situ were higher than what was found over agricultural sites in the United States, where RMSE of 0.03 $m^3 m^{-3}$ were found (Bindlish et al., 2015). This may be due to a number of factors, including the greater diversity of land cover at the selected sites in Canada, and the larger number of in situ measurements available over the footprint of the satellite at the sites in the United States to better characterize the variability in soil moisture over the radiometer footprint. The networks in MB and SK have been well studied to determine that the network averages scale well to the average soil moisture over the radiometer footprint, whereas the ON and AB sites have not been systematically analyzed to determine how well stations represent the area average (Adams et al., 2015).

For many agricultural applications the dry bias observed in SMOS is less of a concern than issues with accurately capturing the temporal trends. As an indicator of relative soil moisture, SMOS and Aquarius both showed a strong relationship with in situ measurements at the Ontario and Saskatchewan sites, a somewhat more mixed representation at the Manitoba site, and a very mixed representation of in situ soil moisture patterns at sites in Alberta (Fig. 3). The RMSE calculated on the relative soil moisture showed that the difference between SMOS and in situ measurements was close to 1.0 standard deviation of the average for all sites (on average for the Alberta sites). The Aquarius soil moisture also, in general, captured the relative trends in soil moisture well, even at the sites in Alberta.

3.2. Impact of variable land cover on soil moisture retrieval from satellite data

The Peace River region in northern Alberta and the Ontario site in eastern Canada contain a substantial amount of forested land, open water bodies and wetlands which may be a source of uncertainty in the soil moisture retrieval. To assess the impact of land cover on soil moisture retrieval, the land cover fractions under each pixel was examined from the National Land Cover Map of Canada (Fisette et al., 2005) for Aquarius and the Data Analysis Parameter (DAP) files for SMOS (Fig. 4). Sites in the northern agricultural regions of Alberta often had few valid observations from either SMOS or Aquarius. An inspection of the SMOS record indicated that in some cases this was due to large water bodies in the vicinity, as well as surface temperatures below zero at the time of acquisition. For the SMOS data, the cRMSE and correlation coefficients were compared with the land cover fractions using a linear correlation analysis (not shown). There was no strong relationship found between these. This suggests that even though there may be higher RMSE with the ground data due to land cover variability within the pixel, other factors (such as the non-representativeness of the stations at the coarser scale) may be more important (Champagne et al., 2014). The relatively high correspondence between in situ and satellite soil moisture for the Ontario site, which has a relatively high fraction of forested, open water and other non-agricultural land cover types suggests that when the soil moisture variability is well-characterized at the sub-grid scale, the difference between soil moisture from the satellite and the in situ data is reduced. At this site, the sensors were located to capture variability in soil texture rather than variability in landcover, with all sites located on agricultural land use areas. The RMSE between ground measurements and SMOS and Aquarius satellite soil moisture were compared to each other (Fig. 5). These were for the most part uncorrelated, with RMSE in Aquarius much higher while RMSE in SMOS soil moisture at the same sites remained relatively low. The correlation coefficients showed a somewhat more distinct pattern, with sites with high correlation for both sensors generally in agreement, but there were several sites where Aquarius had a low correlation and SMOS was relatively high. These sites showed no distinct patterns in terms of land cover, but there did appear to be a high number of points in the Aquarius time series where high soil moisture values were retrieved (greater than 50%). When these are removed, the correlations improved somewhat, but were still poor (the correlations remained below 0.50 and as low as 0.02). This may require some further exploration as to why the Aquarius retrievals were so high over these particular sites. One of the key differences between how each sensor estimates soil moisture is on how the vegetation optical depth is estimated. A comparison of the vegetation optical depth estimated between the two instruments was not possible, since these values were not directly available as comparable values for each sensor, but differences in how the sensors estimate vegetation optical depth and vegetation water content could be explain the variability in how each sensor estimates soil moisture relative to the in situ data. A previous study found a lack of typical seasonal response in the SMOS vegetation optical depth data, and suggested this model estimate may be dependent on factors other than vegetation (Jackson et al., 2012).

3.3. Satellite surface soil moisture as an indicator of agricultural climate conditions

The time series of each satellite soil moisture data set was compared to the in situ measurements in the context of general agricultural climate conditions in these regions (Fig. 6a and b). The Ontario site has a much higher frequency of rainfall events than the other sites, and this is clear from the soil moisture pattern at the surface. The SMOS surface soil moisture managed to capture the frequent wetting and drying cycles at this site over the three year period. There are some periods in 2012 where the SMOS surface moisture does not correspond well to the in situ which, despite wetting events, remained drier than normal for most of the July–September period. This appears to be largely related to an overestimation of the surface wetness shortly after rainfall events. The SMOS data in Manitoba was less consistent, with many of the high frequency wetting and drying periods being estimated incorrectly from SMOS, particularly in 2012 and 2013. In 2013, in particular, the June–August period is greatly underestimated by SMOS, where conditions are actually wetter than normal and SMOS shows these as average or in some cases drier than normal. This may be related to the high soil diversity over this area; the clay soils in this region have less surface soil moisture variability and retain wetness longer than the sandy soils, so the mixed pixel at the SMOS scale is difficult to represent with the existing stations. This may explain why many of the dry extremes in the time series are not well represented by the SMOS data. For the Saskatchewan site, the SMOS data for the most part shows a good agreement with the in situ data, although there is some under-representation of the moisture conditions in 2013. The trend however, is consistent between the two data sets.

For the Aquarius soil moisture, the data at the Ontario site does not capture these daily high frequency wetting/drying patterns as well. Overall, if one looks at the three seasons examined, the 2012 season shows up as drier than the other two for the most part, which is consistent with the surface soil moisture patterns from the in situ, but it is not capturing the magnitude of the dry 2012 season as well as the in situ, with the soil appearing normal to wetter than normal for many dates during that season. For the Manitoba site, the trend is somewhat better, with Aquarius capturing the more prolonged drying sequences and in most cases capturing the wetting cycles, if not the magnitude. This can be seen in the high surface saturation conditions seen in June–July 2014, where the Aquarius values peak over a longer period but do not capture the intensity of the saturation in early July. A similar pattern can be seen in the more arid conditions in Saskatchewan, with the general drying trends captured well by Aquarius. In general, the Aquarius moisture seems to be most consistent with ground measurements in the more arid regions of Saskatchewan and Alberta and is less responsive to high frequency wetting events.

To further illustrate this, an extreme wetness event in Manitoba in 2014 is shown in Fig. 7. This figure shows a period in June–July 2014 where an intense rainfall event on June 29 caused a saturation of the soil at the surface (Fig. 7, bottom). The SMOS acquisitions are more temporally frequent, so these show the wetting and drying event in more detail than the Aquarius data. The SMOS soil moisture on June 10 is shown as slightly lower than average (−0.4 or approximately half a standard deviation below normal, which translates to a soil moisture value of $0.12\,m^3\,m^{-3}$) after a relatively dry spring. This is consistent with what the in situ data is estimating, with the measured value showing the soil moisture 0.5 standard deviations below normal. After some smaller rainfall events in mid-June, the surface soil becomes wetter, and SMOS captures this event relatively well, with moisture rising to 1.6 deviations above average or $0.32\,m^3\,m^{-3}$). After a large rainfall event, the surface soil moisture from SMOS peaks at $0.47\,m^3\,m^{-3}$ or 3.3 deviations above normal from the SMOS, the magnitude of which is consistent with the in situ measurements, with a slight underestimation. The SMOS then shows a dry down, with moisture at 0.8 standard deviation above average on July 7 and 0.2 standard deviation above average by July 15, although SMOS underestimates the extent of the dry-down moving into July. The Aquarius data do show drier than average conditions on June 10, but the wetting event that occurs in mid-June saturates the soil and the moisture remains at that level until mid-July, showing very little change in response to the higher magnitude rainfall event on June 29. This lack of sensitivity of the wet soils to further wetting can be seen at other times and at other locations.

4. Conclusions

SMOS and Aquarius passive microwave derived surface soil moisture were assessed at numerous sites within agricultural areas of Canada. Both data sets showed relatively good sensitivity to general changes measured by in situ soil moisture sensors, with SMOS generally showing a better relationship with the in situ data at most sites. This included the Ontario site, which has significant non-agricultural land within the pixel footprint and where the soil moisture retrieval model for SMOS would be expected to perform less well. The root mean squared errors were less where the subgrid soil moisture was better characterized (sites in Saskatchewan, Manitoba and Ontario). SMOS in some cases overestimates moisture relative to in situ stations shortly after rainfall events, but this was not consistent for each site and each time period. Similarly, underestimation of the magnitude of drying events was found in some cases from SMOS, but this was not consistent from site to site. Changes to the SMOS soil moisture retrieval algorithm since launch as well as the use of a more robust time series for RMSE estimation has shown that the discrepancy between SMOS and in situ is lower than found in previous studies at sites in Canada, and with RMSE less than $0.10\,m^3\,m^{-3}$ in most cases. The Aquarius soil moisture data showed less correspondence with in situ data in areas where there were more frequent wetting and drying cycles, particularly in Ontario and Manitoba and selected sites in Alberta. The Aquarius soil moisture data were more accurate in arid regions and contains some saturation at sites adjacent to the mountain range in Alberta. Overall, both data sets, and SMOS in particular, showed a stable and consistent pattern of capturing surface soil moisture over time. The SMOS data has higher spatial resolution and is available on a more temporally frequent basis, making it a suitable data set for most agricultural applications.

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