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Received 17 January 2008; revised 25 March 2008; accepted 1 April 2008; published XX Month 2008.

[1] Soil moisture (SM) products provided by remote sensing approaches at continental scale are of great importance for land surface modeling and numerical weather prediction. Before using remotely sensed SM products it is crucial to validate them. This paper presents an evaluation of AMSR-E (Advanced Microwave Scanning Radiometer - Earth Observing System) SM products over two sites. They are located in the south-west of France and in the Sahelian part of Mali in West Africa, in the framework of the SMOSREX (Surface Monitoring Of Soil Reservoir Experiment) and AMMA (African Monsoon Multidisciplinary Analysis) projects respectively. The most representative station of the four stations of each site is used for the comparison of AMSR-E derived and in-situ SM measurements in absolute and normalized values. Results suggest that, although AMSR-E SM product is not able to capture absolute SM values, it provides reliable information on surface SM temporal variability, at seasonal and rainy event scale. It is shown, however, that the use of radiometric products, such as polarization ratio, provides better agreement with ground stations than the derived SM products. **Citation:** Gruhier, C., P. de Rosnay, Y. Kerr, E. Mougin, E. Ceschia, J.-C. Calvet, and P. Richaume (2008), Evaluation of AMSR-E soil moisture product based on ground measurements over temperate and semi-arid regions, *Geophys. Res. Lett.*, *35*, LXXXXX, doi:10.1029/2008GL033330.

1. Introduction

[2] Soil moisture (SM) strongly influences and interacts with the land surface processes that control the land surface fluxes. Remote sensing approaches provide spatially integrated information on SM which is valuable information for land surface modeling either in terms of validation or assimilation. Different approaches have been developed for SM remote sensing among which passive microwave at low frequencies is the most promising [*Kerr*, 2007; *Entekhabi et al.*, 2004; *Njoku et al.*, 2003; *Kerr et al.*, 2001; *Njoku and Entekhabi*, 1996; *Engman*, 1990].

[3] The future SMOS (Soil Moisture and Ocean Salinity), is the first mission specifically devoted to SM remote sensing over land surfaces [*Kerr et al.*, 2001]. It will provide measurements of brightness temperature (TB) at L-band, which is shown to be highly sensitive to surface SM with less sensitivity to vegetation cover.

[4] The Advanced Microwave Scanning Radiometer on Earth Observing System (AMSR-E) of AQUA satellite, is a multi-channel passive microwave instrument. It was launched in 2002 to measure TB at five frequencies in the range of 6.9 to 89 GHz.

[5] Before using remotely sensed SM products it is crucial to validate and characterize their ability to provide quantitative estimates of SM. In this study, data from AMSR-E are evaluated. The full year 2005 is considered, which allows investigating AMSR-E suitability at rainfall event and drying cycle temporal scale, as well as at seasonal and inter-seasonal scales.

[6] Two sites are used for validating AMSR-E products under contrasted surface and weather conditions, in Europe with the SMOSREX (Surface Monitoring Of Soil Reservoir Experiment) project and in Sahel with the AMMA (African Monsoon Multidisciplinary Analysis) project. The arrangement of the SM measuring sites was specifically designed to address the validation of remotely sensed SM. The AMMA-Mali site allows providing an evaluation of AMSR-E SM products in Sahelian area where SM remote sensing is of great importance to investigate feedbacks between SM and precipitation [*Koster et al.*, 2004].

[7] AMSR-E SM products and polarization ratio are evaluated against the best representative SM station of each site. Detailed analysis is conducted to evaluate AMSR-E skill to capture SM peak linked to rainfall events occurrence and SM temporal dynamics from season to year.

2. Study Regions and Data

[8] Table 1 provides information on the stations locations, as well as the availability of surface SM data at 5-cm depth for Day of Year (DOY) 2005.

2.1. SMOSREX

[9] SMOSREX site is located about 30 km south of Toulouse in France. It aims at developing and improving the direct and inverse algorithms for SM retrieval from L-band radiometry [*de Rosnay et al.*, 2006]. This site includes two stations (SMB, SMF). Two additional stations, Auradé (AUR) and Lamasquère (LAM) (CarboEurope-IP network, [*Dolman et al.*, 2006]) are used (Table 1).

[10] The four stations allow documenting SM in different soil texture and vegetation cover conditions. While SMB, SMF and AUR stations are located on medium loamy textured soils, LAM is on a more clay soil along the Touch river. Vegetation cover are very various with either different types of crops (dominant land use) such as rape (AUR) and triticale (LAM), bare soil (SMB) or natural grass (SMF).

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0094-8276/08/2008GL033330$05.00

Table 1. SM Stations Location and Data Availability for SMOSREX and AMMA-Mali Sites

Location	Station Name	Latitude	Longitude	Start DOY 2005	End DOY 2005	DOY Missing
			SMOSREX			
Auradé	AUR	43.54°N	1.10°E	1	365	327–349
Lamasquère	LAM	43.49°N	1.23°E	1	365	103–110, 128–132
SMOSREX Bare soil	SMB	43.38°N	1.28°E	1	365	20,231–240,252–257
SMOSREX Fallow	SMF	43.38°N	1.28°E	1	365	17–32
			AMMA-Mali Sites			
Agoufou bottom	AGB	15.34°N	1.47°E	105	365	None
Agoufou top	AGT	15.34°N	1.47°E	44	365	179–180
Bangui Mallam	BAG	15.39°N	1.34°E	102	320	None
Eguérit	EGU	15.50°N	1.39°E	105	321	None

[11] SMOSREX site is located in a temperate climatic region, with well contrasted annual cycle of air temperature and precipitation. 2003–2005 period was characterized by particularly dry conditions. The cumulated rainfall for 2005 was 480 mm (Figure 1).

2.2. AMMA-Mali

[12] The AMMA program aims at improving the comprehension of the African monsoon dynamics at seasonal to inter-annual temporal scales [*Redelsperger et al.*, 2006]. The Mali site is focused on surface processes, remote sensing of vegetation and SM. Four calibrated and checked SM stations (Table 1) from the super-site are used. They monitored SM at a 15-minute time step. 65% of the studied region is characterized by undulating dune systems with moderate slopes represented by three stations: AGT at the top of a hillslope, BAG at intermediate elevation and AGB in bottom. In contrast, the EGU station is implemented on a flat rocky-loam plain representing 30% of the region.

[13] The AMMA-Mali site is located in the semi-arid Sahelian area. Climatic conditions are governed by the West African Monsoon with a long dry season and a shorter rainy season from July to September (Table 1). The AMMA-Mali site is characterized by a mean annual rainfall of 370 mm per year (over 1920–2005). In 2005, monsoon dynamics allowed to have substantial rainfall and the cumulated rainfall reached 441 mm, of which 390 mm occurred in June–September.

2.3. AMSR-E Spacebased Measurements

[14] The AMSR-E is a multi-channel passive microwave instrument, on the Aqua satellite launched in May 2002. It operates in polar sun-synchronous orbit with equator crossings at 1:30 pm/am local solar time for ascending/descending orbits. Global coverage is achieved every two days or less depending on the latitude. AMSR-E operates at an incidence angle of 55° at frequencies of 6.9, 10.7, 18.7, 23.8, 36.5 and 89 GHz, all with H and V polarizations. The data used are NASA level 3 where daily average of TB and SM products, re-sampled to a global cylindrical 25 km Equal-Area Scalable Earth Grid (EASE-Grid) cell spacing.

[15] AMSR-E Radio-Frequency Interference (RFI) are shown to affect large areas in North America and Japan at C-band, while X-band signal is contaminated in England, Italy and Japan [*Njoku et al.*, 2005]. As a consequence the original C and X-band retrieval algorithm was revised to operate using only X-band. This leads to decreased performances in SM retrieval. In this study AMSR-E volumetric SM products are used, as well as TB at 6.9 and 10.7 GHz at horizontal and vertical polarizations.

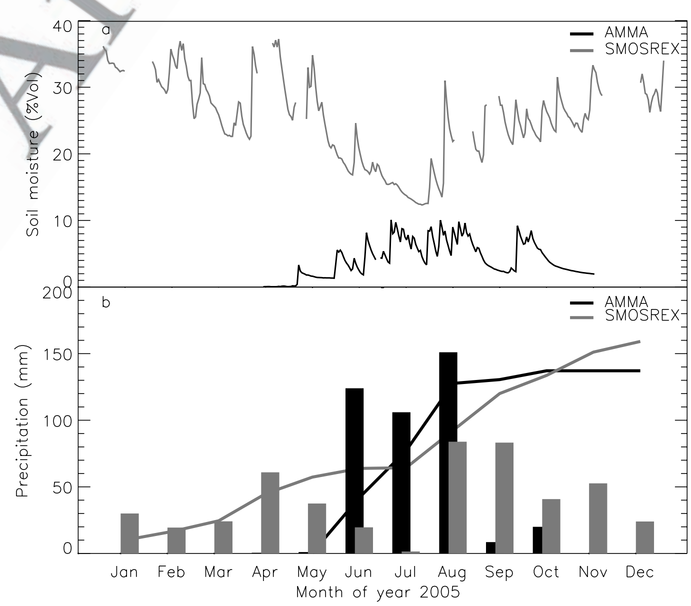


Figure 1. Annual cycle of (a) mean daily SM of all stations and (b) monthly mean and cumulated precipitation over SMOSREX (grey) and AMMA-Mali (black) sites.

Table 2. Mean Relative Difference and Its Standard Deviation, of the Surface SM on AMMA and SMOSREX Sites[a]

	SMOSREX			
	SMB	AUR	SMF	LAM
Range	1	2	3	4
MRD	−0.197	−0.035	0.041	0.191
STD	0.150	0.115	0.228	0.170
	AMMA-Mali			
	AGT	BAG	AGB	EGU
Range	1	2	3	4
MRD	−0.591	−0.360	0.008	0.942
STD	0.294	0.442	0.539	0.895

[a]In % m^3 m^{-3}.

[16] According to [*Njoku et al.*, 2003], the H and V polarizations enable calculation of the polarization ratio (PR), which reduces the effects of soil temperature:

$$PR = \frac{TB_v - TB_h}{TB_v + TB_h} \tag{1}$$

The PR dynamics is mainly linked to SM and vegetation water content (VWC). But it must be interpreted with caution because SM and VWC have opposite effect on PR dynamics.

[17] In order to cover the ground measurement sites, the four-pixel average is used in the following analysis to evaluate AMSR-E products against ground measurements. Due to the AMSR-E products re-sampling, SM values of adjacent pixels are strongly correlated each other (94% fir the two sites), with very low Root Mean Square Error (RMSE) of 0.38% $m^3.m^{-3}$.

3. Spatial Feature of Ground Soil Moisture

[18] The most representative station can be identified with the methodology from *Vachaud et al.* [1985]. Based on statistical index of Mean Relative Difference (MRD). The use of the most representative station provides similar results to those obtained with the values of the four stations. But it allows to eliminate the accumulation of missing data. Best performance to represent the network average is obtained for a MRD value of zero. Stations with negative (positive) values of MRD underestimate (overestimate) surface SM. Standard deviation (STD) of MRD provides information on the temporal stability of station. Lowest STD and lowest absolute value of MRD indicate the most representative station which is able to capture both temporal variability and mean value of SM (Table 2). Thus, AUR station as the most representative station. Surface SM temporal dynamics, is a crucial component of the land surface processes that controls the surface-atmosphere interactions on different temporal scales ranging from diurnal scale to seasonal and annual scales. Here the representativity of a station is evaluated by considering its ability to capture the surface SM dynamics. Accordingly, the AGT station, with smallest STD, is the best representative station of temporal dynamics of SM of the studied region.

4. AMSR-E Soil Moisture Product Evaluation

[19] AMSR-E data and ground data from the best representative SM station are temporally co-located with a 15-minute time step. Quantitative results of their comparison are provided in Table 3.

[20] For seasonal analysis, the year is split in four periods. According to the monsoon timing they are chosen as January–February–March (JFM), April–May–June (AMJ), July–August–September (JAS) and October–November–December (OND).

4.1. SMOSREX

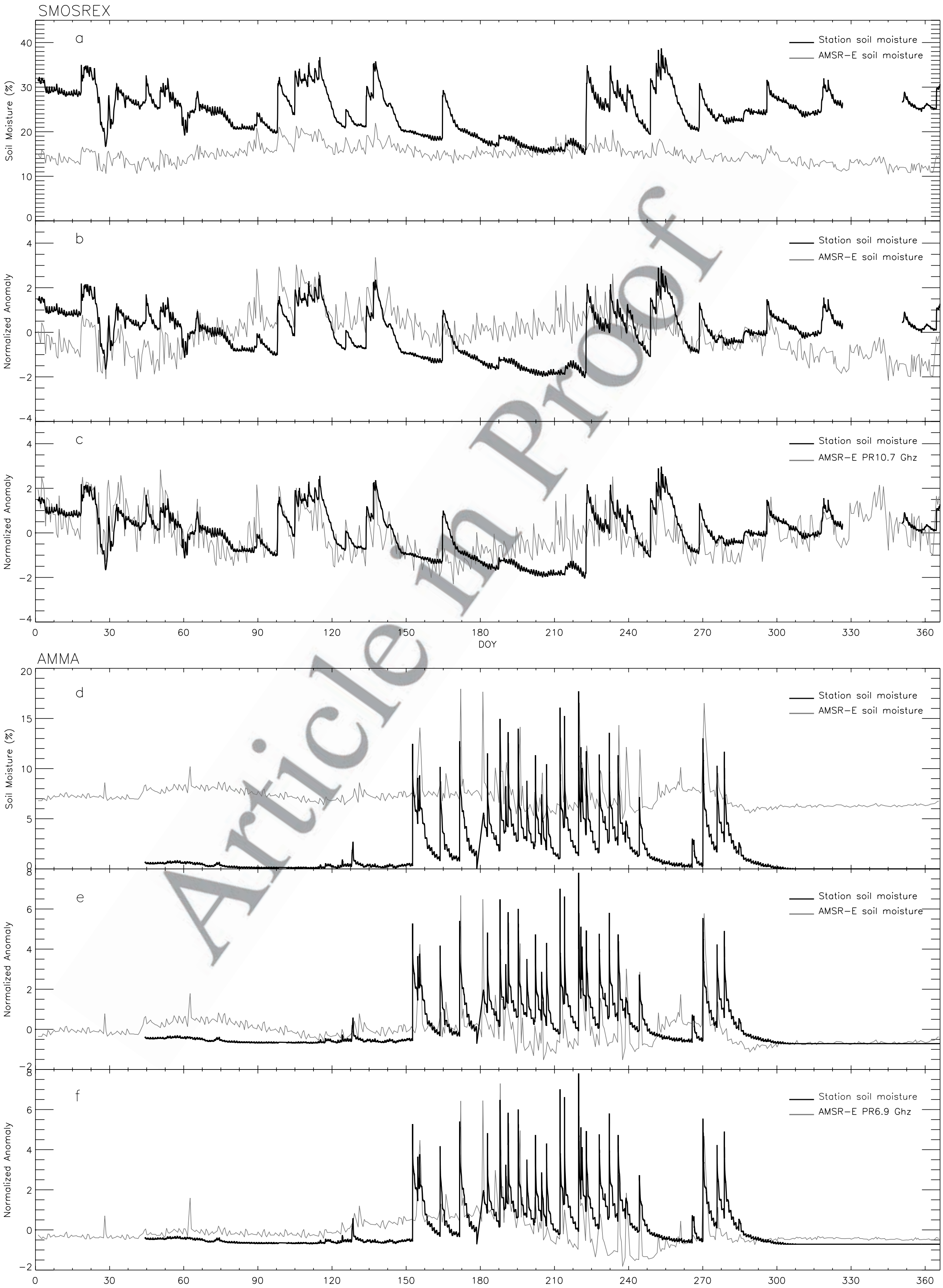
[21] Figure 2a shows the temporal evolution of ground based and AMSR-E SM products. AMSR-E SM values are largely underestimated compared to those from ground measurements. The annual mean value of AMSR-E SM bias is −9.63% in volumetric SM. The largest bias is reached in fall and winter with −12.0% and −12.3% for OND and JFM, respectively. Temporal variability of AMSR-E SM products is also underestimated at the various temporal scales. The amplitude of the SM annual cycle is 11.35% for AMSR-E SM against 21.48% for the ground measurements. In addition, the AMSR-E SM products appear to be relatively noisy making the separation of moderate SM increases from noise difficult.

[22] Normalized anomaly of surface SM is shown in Figure 2b for both AMSR-E products and ground measurements. It is defined as the difference to the annual mean

Table 3. Comparison Between the Best Representative Ground Station and Different AMSR-E Products: SM and PR at 6.9 GHz and 10.7 GHz, at Annual and Seasonal Scales

		SM					
Period	Site	RMSE, % m^3 m^{-3}	Bias, % m^3 m^{-3}	*R*, %	PR6.9 *R*, %	PR10.7 *R*, %	Number of Data
YEAR	SMOSREX	10.8	−9.6	17.3[a]	60.4[a]	61.4[a]	491
	AMMA	6.1	5.9	54.3[a]	59.3[a]	44.6[a]	387
JFM	SMOSREX	12.9	−12.3	2.1	59.6[a]	65.8[a]	144
	AMMA	7.7	7.7	24.6	20.9	−1.1	58
AMJ	SMOSREX	8.7	−7.9	81.1[a]	74.8[a]	78.9[a]	132
	AMMA	6.5	6.3	62.9[a]	72.7[a]	73.4[a]	103
JAS	SMOSREX	8.8	−6.8	21.5	51.0[a]	42.4[a]	122
	AMMA	5.2	4.7	53.5[a]	66.7[a]	60.6[a]	114
OND	SMOSREX	12.2	−12.0	4.7	49.2[a]	68.7[a]	93
	AMMA	5.9	5.9	73.5[a]	63.7[a]	32.4	112

[a]Significant correlation values, with a confidence level higher than 99.9% (e.g., with an error risk of 0.001), according to the number of co-located data used for each.



SMOSREX
a
b
c
Station soil moisture
AMSR-E soil moisture
AMSR-E PR10.7 Ghz
Soil Moisture (%)
Normalized Anomaly
DOY
AMMA
d
e
f
AMSR-E PR6.9 Ghz

Figure 2

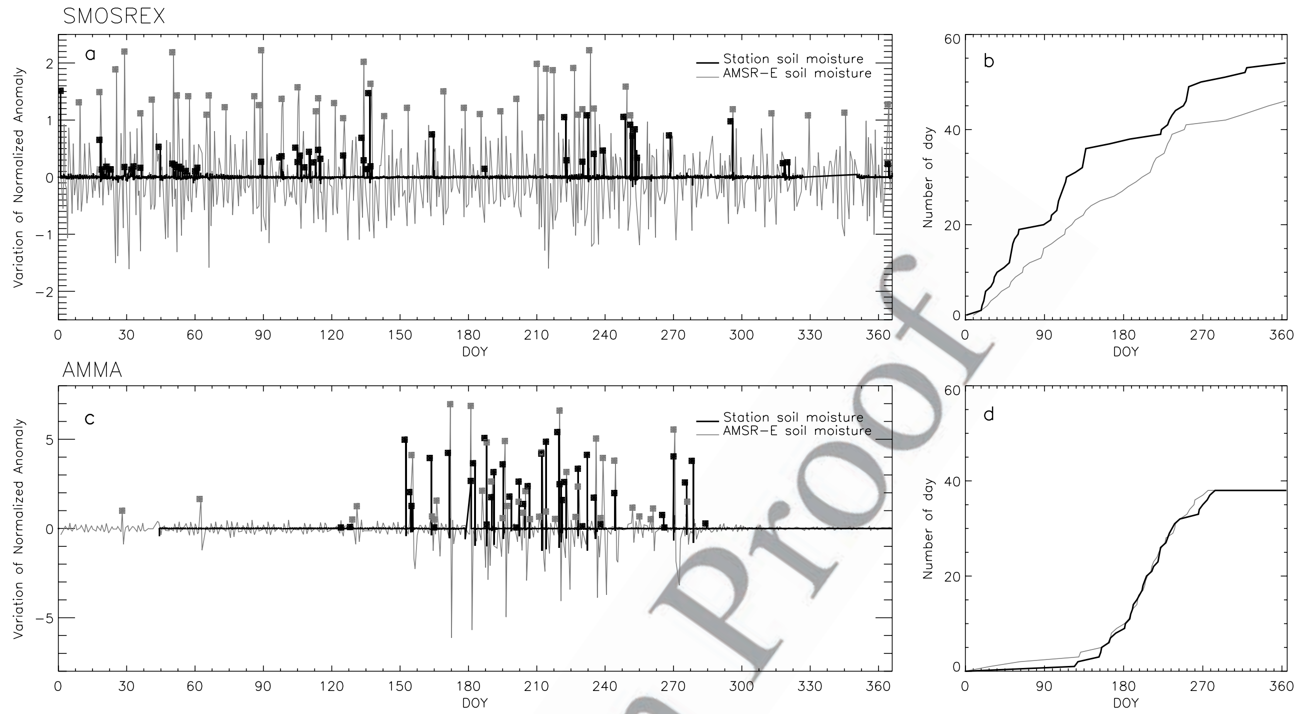


Figure 3. (left) Increments of standardized anomaly of SM from ground station (black) and AMSR-E product (grey), over (a) and (b) SMOSREX and (c) and (d) AMMA-Mali. Significant increments are indicated by a square. (right) Cumulated number days with significant positive increments.

divided by the standard deviation of the time series. Despite quite large noise, AMSR-E SM product provides good agreement with ground data in term of temporal variability. Table 3 indicates a significant correlation of 17.3% with an error risk at 0.001, which is a good result according to diversity of climate conditions. The AMSR-E performances vary with the seasons ranging from 2.1% in JFM, to 81.1% in AMJ. In JAS, SM and VWC decrease. Accordingly, their contribution to the microwaves signal are opposite. SM dynamics contributes to increase TB while vegetation dynamics leads to decrease TB. In OND, poor correlation are not due to frozen event occurrence. During this season, SM and VWC increase, leading again to opposite effect on TB dynamics. In this conditions, where seasonal trend of SM and VWC are correlated, SM retrieval is made very challenging and requires to account with accuracy for the vegetation effect on the signal [*de Rosnay et al.*, 2006]. These results show that the suitability of AMSR-E SM products to depict SM dynamics is depending on the season.

[23] In contrast to SM products, PR at both 6.9 GHz and 10.7 GHz are well correlated with the in-situ observations. At the annual scale correlation values are 60.4% and 61.4% at C and X-band, respectively. Results at the seasonal scale also indicate significant correlation values for any term of the year for both frequencies. The best agreement is provided by X-band measurements in spring time (AMJ), with a 78.9% correlation, as clearly shown in Figure 2c. This indicates the suitability of AMSR-E PR products to capture normalized SM dynamics over this site at seasonal and annual scales.

[24] Figure 3a shows the ability of AMSR-E products to capture SM variations at the precipitation event scale. Based on normalized SM anomalies, a threshold is used to filter out signal noise and low SM increases from significant SM variations. Based on data monitored during dry period it is fixed to be 0.1 for ground measurements and 1.0 for AMSR-E SM products. Positive increments larger than the threshold, represented by squares on the figure, are related to relatively important precipitation occurrence. Figure 3b shows the cumulated number of days where positive SM increments is obtained, for both AMSR-E and ground measurements of SM. Ground measurements indicate 54 days with significant positive increments. According to field observation of precipitation, they correspond to precipitation events larger than 2 mm, which represent 90% of the annual rainfall.

4.2. AMMA-Mali

[25] Similar analysis is conducted for the AMMA-Mali site. AMSR-E product, which is overestimated, does not capture the correct range of SM (Figure 2 (bottom)). Bias on volumetric SM is 5.9% at the annual scale (Table 3). The lower bias is obtained during rainy season and the higher bias is obtained during dry season (4.7% in JAS and 7.7% in JFM). AMSR-E SM product presents a minimum SM threshold, which is inconsistently higher during the dry

Figure 2. Comparison for (top) SMOSREX and (bottom) AMMA-Mali between the best representative station (black) and AMSR-E product (grey): (a) and (d) SM absolute values, (b) and (e) SM normalized values, and (c) and (f) PR normalized values.

season (about 7%) than during then rainy season (about 5%). Despite of this, the annual cycle of AMSR-E volumetric SM product is shown to capture large SM increases related to strong precipitation events occurring in the monsoon season.

[26] Normalized values of SM are shown in Figure 2e. Corresponding significant correlation is indicated in Table 3 to be 54.3%. Lower values of correlation are obtained in dry season (24.6% in JFM) due to signal noise which is larger than SM variations in this season. But significant correlation values obtained in AMJ (62.9%), JAS (53.5%) and OND (73.5%) are particularly noteworthy when SM dynamics is more important. All of the correlation values are significant, indicating that AMSR-E SM products is able to capture efficiently the SM dynamics over this Sahelian site, at both annual and seasonal scales.

[27] PR products are significantly correlated to ground SM at the annual scale, with values of 59.3% and 44.6% for C-band and X-band respectively. As for SM products, best agreement between PR and ground SM are obtained during the monsoon season, with correlation values of 66.7% at C-band and 60.6% at X-band. Figure 2f confirms this good agreement, showing normalized C-band PR and ground SM.

[28] Figure 3c shows the evaluation of AMSR-E SM products at the rainfall event scale. For this site, the minimum threshold to consider increments of normalized SM is determined based on dry season data to be 0.05 and 0.5 for ground station and AMSR-E SM product, respectively. AMSR-E SM product indicate that 38 days of the year present a positive increment, also detected by ground measurements, which is consistent with precipitation data. Moreover, a very good agreement concerning their temporal distribution is shown by Figure 3d. Accordingly AMSR-E SM product is shown to capture with a high degree of accuracy the occurrence of SM increases at the precipitation event scale over AMMA-Mali.

5. Conclusion

[29] This paper investigates the ability of AMSR-E products provided by the NASA, to capture the ground SM over two sites.

[30] For both sites AMSR-E SM products and polarization ratio are shown to be noisy, particularly at the daily scale, and the absolutes values of SM are not captured (Figures 2a and 2d). Ground measurements are underestimated by AMSR-E SM product over the SMOSREX site and overestimated over the AMMA-Mali site (Table 3). The amplitude of volumetric SM provided AMSR-E products, is shown to be underestimated over both sites. Nevertheless, AMSR-E SM product captures the SM temporal variability (Figures 2b and 2e).

[31] However, this paper shows that polarization ratios at C and X-band are more suitable than SM product to capture the SM dynamics over the two sites. Indeed, due to serious contamination by RFI, multi-source information provided by the different operating frequencies of AMSR-E is not fully used in the NASA AMSR-E processing chain. In particular, C-band data, which are highly relevant for SM retrieval, are not used, limiting thereby the performances of the algorithm.

[32] At the precipitation event scale, it is shown that AMSR-E performs very well to detect occurrence of SM variation over AMMA-Mali site, with a perfect agreement of the timing as shown by the Figures 3c and 3d. This good performance is particularly noteworthy and very promising for the use of AMSR-E product in Sahelian area.

[33] The results presented in this paper clearly show that, (1) the polarization ratio product is in better agreement with ground measurements than SM products (2) ability of AMSR-E to retrieve SM in the studied temperate areas must be taken with care but temporal variability of surface SM is captured by the PR, (3) AMSR-E is highly suitable for SM remote sensing over semi-arid areas. It is shown to capture the SM variability in term of normalized SM values, at any temporal scale.

[34] The future SMOS sensor, with higher sensitivity to SM due to L-band measurements, is expected to provide improved accuracy in SM variability retrieval, as well as in term of volumetric SM.

[35] **Acknowledgments.** The authors thank the SMOSREX and CarboEurope-IP field experiments. Based on a French initiative, AMMA was built by an international scientific group and is currently funded by a large number of agencies, especially from France, the UK, the US, and Africa. It has been the beneficiary of a major financial contribution from the European Community's Sixth Framework Research Programme (http://www.amma-international.org).

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