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2 Evaluation of AMSR-E soil moisture product based on ground 3 measurements over temperate and semi-arid regions

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8 [1] Soil moisture (SM) products provided by remote
9 sensing approaches at continental scale are of great
10 importance for land surface modeling and numerical
11 weather prediction. Before using remotely sensed SM
12 products it is crucial to validate them. This paper presents
13 an evaluation of AMSR-E (Advanced Microwave Scanning
14 Radiometer - Earth Observing System) SM products over
15 two sites. They are located in the south-west of France and
16 in the Sahelian part of Mali in West Africa, in the
17 framework of the SMOSREX (Surface Monitoring Of Soil
18 Reservoir Experiment) and AMMA (African Monsoon
19 Multidisciplinary Analysis) projects respectively. The most
20 representative station of the four stations of each site is
21 used for the comparison of AMSR-E derived and in-situ
22 SM measurements in absolute and normalized values.
23 Results suggest that, although AMSR-E SM product is not
24 able to capture absolute SM values, it provides reliable
25 information on surface SM temporal variability, at
26 seasonal and rainy event scale. It is shown, however,
27 that the use of radiometric products, such as polarization
28 ratio, provides better agreement with ground stations than
29 the derived SM products. **Citation:** Gruhier, C., P. de Rosnay,
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35 1. Introduction

36 [2] Soil moisture (SM) strongly influences and interacts
37 with the land surface processes that control the land surface
38 fluxes. Remote sensing approaches provide spatially inte-
39 grated information on SM which is valuable information for
40 land surface modeling either in terms of validation or
41 assimilation. Different approaches have been developed
42 for SM remote sensing among which passive microwave
43 at low frequencies is the most promising [Kerr, 2007;
44 Entekhabi et al., 2004; Njoku et al., 2003; Kerr et al.,
45 2001; Njoku and Entekhabi, 1996; Engman, 1990].

46 [3] The future SMOS (Soil Moisture and Ocean Salinity),
47 is the first mission specifically devoted to SM remote
48 sensing over land surfaces [Kerr et al., 2001]. It will provide
49 measurements of brightness temperature (TB) at L-band,
50 which is shown to be highly sensitive to surface SM with
51 less sensitivity to vegetation cover.

[4] The Advanced Microwave Scanning Radiometer on 52
Earth Observing System (AMSR-E) of AQUA satellite, is a 53
multi-channel passive microwave instrument. It was 54
launched in 2002 to measure TB at five frequencies in the 55
range of 6.9 to 89 GHz. 56

[5] Before using remotely sensed SM products it is 57
crucial to validate and characterize their ability to provide 58
quantitative estimates of SM. In this study, data from 59
AMSR-E are evaluated. The full year 2005 is considered, 60
which allows investigating AMSR-E suitability at rainfall 61
event and drying cycle temporal scale, as well as at seasonal 62
and inter-seasonal scales. 63

[6] Two sites are used for validating AMSR-E products 64
under contrasted surface and weather conditions, in Europe 65
with the SMOSREX (Surface Monitoring Of Soil Reservoir 66
Experiment) project and in Sahel with the AMMA (African 67
Monsoon Multidisciplinary Analysis) project. The arrange- 68
ment of the SM measuring sites was specifically designed to 69
address the validation of remotely sensed SM. The AMMA- 70
Mali site allows providing an evaluation of AMSR-E SM 71
products in Sahelian area where SM remote sensing is of 72
great importance to investigate feedbacks between SM and 73
precipitation [Koster et al., 2004]. 74

[7] AMSR-E SM products and polarization ratio are 75
evaluated against the best representative SM station of each 76
site. Detailed analysis is conducted to evaluate AMSR-E 77
skill to capture SM peak linked to rainfall events occurrence 78
and SM temporal dynamics from season to year. 79

2. Study Regions and Data 80

[8] Table 1 provides information on the stations loca- 81
tions, as well as the availability of surface SM data at 5-cm 82
depth for Day of Year (DOY) 2005. 83

2.1. SMOSREX 85

[9] SMOSREX site is located about 30 km south of 86
Toulouse in France. It aims at developing and improving 87
the direct and inverse algorithms for SM retrieval from 88
L-band radiometry [de Rosnay et al., 2006]. This site 89
includes two stations (SMB, SMF). Two additional stations, 90
Auradé (AUR) and Lamasquère (LAM) (CarboEurope-IP 91
network, [Dolman et al., 2006]) are used (Table 1). 92

[10] The four stations allow documenting SM in different 93
soil texture and vegetation cover conditions. While SMB, 94
SMF and AUR stations are located on medium loamy 95
textured soils, LAM is on a more clay soil along the Touch 96
river. Vegetation cover are very various with either different 97
types of crops (dominant land use) such as rape (AUR) and 98
triticale (LAM), bare soil (SMB) or natural grass (SMF). 99

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t1.1 **Table 1.** SM Stations Location and Data Availability for SMOSREX and AMMA-Mali Sites

t1.2	Location	Station Name	Latitude	Longitude	Start DOY 2005	End DOY 2005	DOY Missing
t1.3	<i>SMOSREX</i>						
t1.4	Auradé	AUR	43.54°N	1.10°E	1	365	327–349
t1.5	Lamasquère	LAM	43.49°N	1.23°E	1	365	103–110, 128–132
t1.6	SMOSREX Bare soil	SMB	43.38°N	1.28°E	1	365	20,231–240,252–257
t1.7	SMOSREX Fallow	SMF	43.38°N	1.28°E	1	365	17–32
t1.8	<i>AMMA-Mali Sites</i>						
t1.9	Agoufou bottom	AGB	15.34°N	1.47°E	105	365	None
t1.10	Agoufou top	AGT	15.34°N	1.47°E	44	365	179–180
t1.11	Bangui Mallam	BAG	15.39°N	1.34°E	102	320	None
t1.12	Eguérit	EGU	15.50°N	1.39°E	105	321	None

100 [11] SMOSREX site is located in a temperate climatic
 101 region, with well contrasted annual cycle of air temperature
 102 and precipitation. 2003–2005 period was characterized by
 103 particularly dry conditions. The cumulated rainfall for 2005
 104 was 480 mm (Figure 1).

105 2.2. AMMA-Mali

106 [12] The AMMA program aims at improving the com-
 107 prehension of the African monsoon dynamics at seasonal to
 108 inter-annual temporal scales [Redelsperger *et al.*, 2006].
 109 The Mali site is focused on surface processes, remote
 110 sensing of vegetation and SM. Four calibrated and checked
 111 SM stations (Table 1) from the super-site are used. They
 112 monitored SM at a 15-minute time step. 65% of the studied
 113 region is characterized by undulating dune systems with
 114 moderate slopes represented by three stations: AGT at the
 115 top of a hillslope, BAG at intermediate elevation and AGB
 116 in bottom. In contrast, the EGU station is implemented on a
 117 flat rocky-loam plain representing 30% of the region.

118 [13] The AMMA-Mali site is located in the semi-arid
 119 Sahelian area. Climatic conditions are governed by the West
 120 African Monsoon with a long dry season and a shorter rainy
 121 season from July to September (Table 1). The AMMA-Mali
 122 site is characterized by a mean annual rainfall of 370 mm
 123 per year (over 1920–2005). In 2005, monsoon dynamics

124 allowed to have substantial rainfall and the cumulated
 125 rainfall reached 441 mm, of which 390 mm occurred in
 126 June–September.

127 2.3. AMSR-E Spacebased Measurements

128 [14] The AMSR-E is a multi-channel passive microwave
 129 instrument, on the Aqua satellite launched in May 2002. It
 130 operates in polar sun-synchronous orbit with equator
 131 crossings at 1:30 pm/am local solar time for ascending/
 132 descending orbits. Global coverage is achieved every two
 133 days or less depending on the latitude. AMSR-E operates at
 134 an incidence angle of 55° at frequencies of 6.9, 10.7, 18.7,
 135 23.8, 36.5 and 89 GHz, all with H and V polarizations. The
 136 data used are NASA level 3 where daily average of TB and
 137 SM products, re-sampled to a global cylindrical 25 km
 138 Equal-Area Scalable Earth Grid (EASE-Grid) cell spacing.

139 [15] AMSR-E Radio-Frequency Interference (RFI) is
 140 shown to affect large areas in North America and Japan at
 141 C-band, while X-band signal is contaminated in England,
 142 Italy and Japan [Njoku *et al.*, 2005]. As a consequence the
 143 original C and X-band retrieval algorithm was revised to
 144 operate using only X-band. This leads to decreased per-
 145 formances in SM retrieval. In this study AMSR-E volu-
 146 metric SM products are used, as well as TB at 6.9 and
 147 10.7 GHz at horizontal and vertical polarizations.

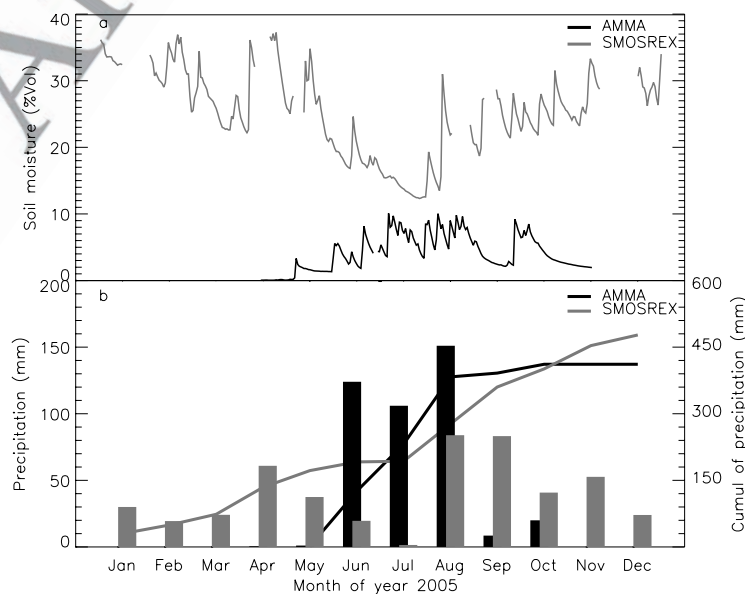


Figure 1. Annual cycle of (a) mean daily SM of all stations and (b) monthly mean and cumulated precipitation over SMOSREX (grey) and AMMA-Mali (black) sites.

t2.1 **Table 2.** Mean Relative Difference and Its Standard Deviation, of
the Surface SM on AMMA and SMOSREX Sites^a

		SMOSREX			
		SMB	AUR	SMF	LAM
t2.4	Range	1	2	3	4
t2.5	MRD	-0.197	-0.035	0.041	0.191
t2.6	STD	0.150	0.115	0.228	0.170
		AMMA-Mali			
		AGT	BAG	AGB	EGU
t2.9	Range	1	2	3	4
t2.10	MRD	-0.591	-0.360	0.008	0.942
t2.11	STD	0.294	0.442	0.539	0.895

t2.12 ^aIn % m³ m⁻³.

148 [16] According to [Njoku *et al.*, 2003], the H and V
149 polarizations enable calculation of the polarization ratio
150 (PR), which reduces the effects of soil temperature:

$$PR = \frac{TB_v - TB_h}{TB_v + TB_h} \quad (1)$$

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

156 [17] In order to cover the ground measurement sites, the
157 four-pixel average is used in the following analysis to
158 evaluate AMSR-E products against ground measurements.
159 Due to the AMSR-E products re-sampling, SM values of
160 adjacent pixels are strongly correlated each other (94% fir
161 the two sites), with very low Root Mean Square Error
162 (RMSE) of 0.38% m³.m⁻³.

164 3. Spatial Feature of Ground Soil Moisture

165 [18] The most representative station can be identified
166 with the methodology from *Vachaud et al.* [1985]. Based
167 with statistical index of Mean Relative Difference (MRD).
168 The use of the most representative station provides similar
169 results to those obtained with the values of the four stations.
170 But it allows to eliminate the accumulation of missing data.
171 Best performance to represent the network average is
172 obtained for a MRD value of zero. Stations with negative
173 (positive) values of MRD underestimate (overestimate)

surface SM. Standard deviation (STD) of MRD provides 174
information on the temporal stability of station. Lowest 175
STD and lowest absolute value of MRD indicate the most 176
representative station which is able to capture both temporal 177
variability and mean value of SM (Table 2). Thus, AUR 178
station as the most representative station. Surface SM 179
temporal dynamics, is a crucial component of the land 180
surface processes that controls the surface-atmosphere inter- 181
actions on different temporal scales ranging from diurnal 182
scale to seasonal and annual scales. Here the representativity 183
of a station is evaluated by considering its ability to capture 184
the surface SM dynamics. Accordingly, the AGT station, 185
with smallest STD, is the best representative station of 186
temporal dynamics of SM of the studied region. 187

4. AMSR-E Soil Moisture Product Evaluation 189

[19] AMSR-E data and ground data from the best 190
representative SM station are temporally co-located with 191
a 15-minute time step. Quantitative results of their com- 192
parison are provided in Table 3. 193

[20] For seasonal analysis, the year is split in four 194
periods. According to the monsoon timing they are chosen 195
as January–February–March (JFM), April–May–June 196
(AMJ), July–August–September (JAS) and October– 197
November–December (OND). 198

4.1. SMOSREX 199

[21] Figure 2a shows the temporal evolution of ground 200
based and AMSR-E SM products. AMSR-E SM values are 201
largely underestimated compared to those from ground 202
measurements. The annual mean value of AMSR-E SM 203
bias is -9.63% in volumetric SM. The largest bias is 204
reached in fall and winter with -12.0% and -12.3% for 205
OND and JFM, respectively. Temporal variability of 206
AMSR-E SM products is also underestimated at the various 207
temporal scales. The amplitude of the SM annual cycle is 208
11.35% for AMSR-E SM against 21.48% for the ground 209
measurements. In addition, the AMSR-E SM products 210
appear to be relatively noisy making the separation of 211
moderate SM increases from noise difficult. 212

[22] Normalized anomaly of surface SM is shown in 213
Figure 2b for both AMSR-E products and ground measure- 214
ments. It is defined as the difference to the annual mean 215

t3.1 **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		R, %	PR6.9 R, %	PR10.7 R, %	Number of Data
t3.3	Period	Site	RMSE, % m ³ m ⁻³				
t3.4	YEAR	SMOSREX	10.8	-9.6	17.3 ^a	60.4 ^a	491
t3.5		AMMA	6.1	5.9	54.3 ^a	59.3 ^a	387
t3.6	JFM	SMOSREX	12.9	-12.3	2.1	59.6 ^a	144
t3.7		AMMA	7.7	7.7	24.6	20.9	58
t3.8	AMJ	SMOSREX	8.7	-7.9	81.1 ^a	74.8 ^a	132
t3.9		AMMA	6.5	6.3	62.9 ^a	72.7 ^a	103
t3.10	JAS	SMOSREX	8.8	-6.8	21.5	51.0 ^a	122
t3.11		AMMA	5.2	4.7	53.5 ^a	66.7 ^a	114
t3.12	OND	SMOSREX	12.2	-12.0	4.7	49.2 ^a	93
t3.13		AMMA	5.9	5.9	73.5 ^a	63.7 ^a	112

t3.14 ^aSignificant 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.

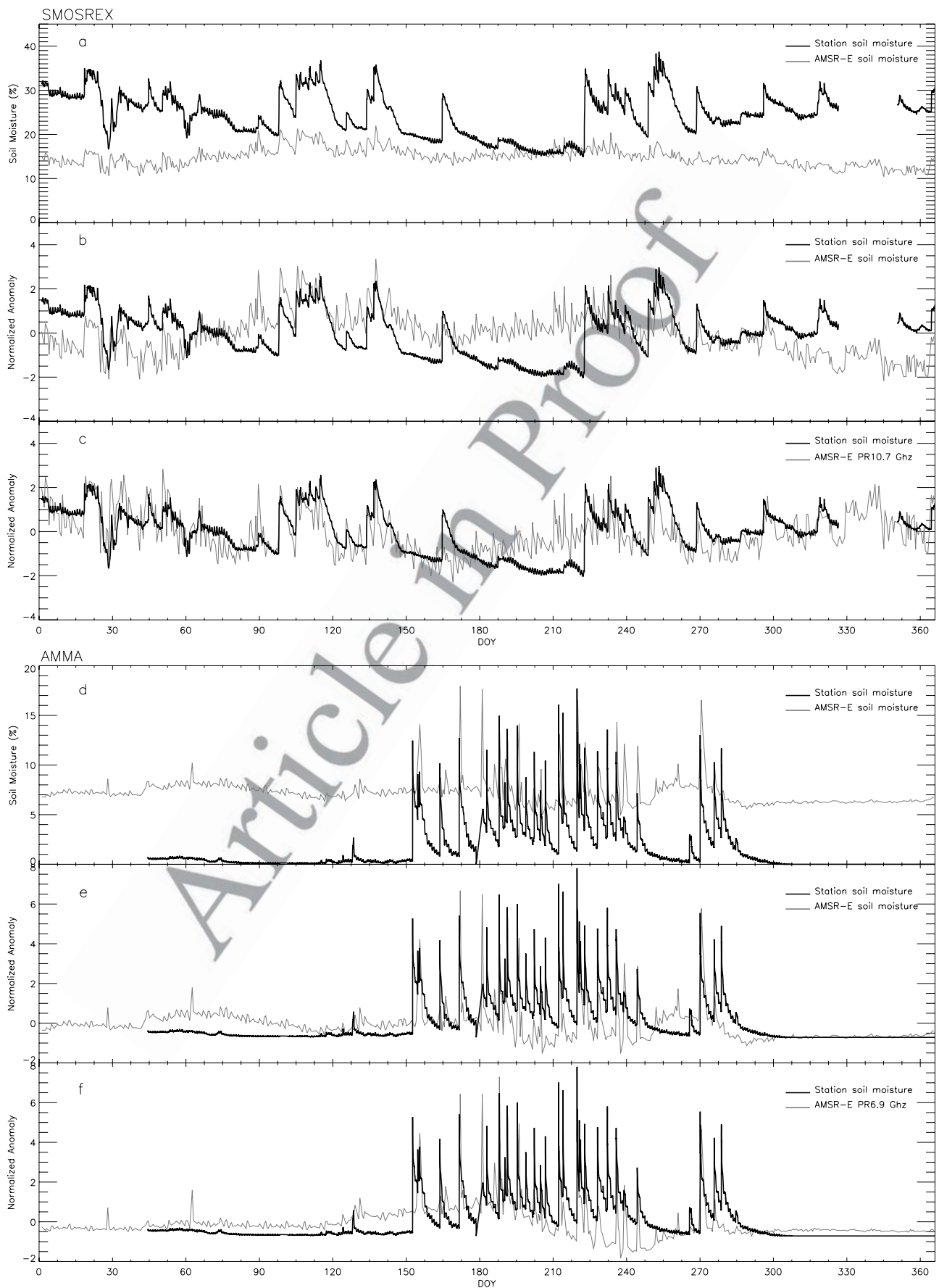


Figure 2

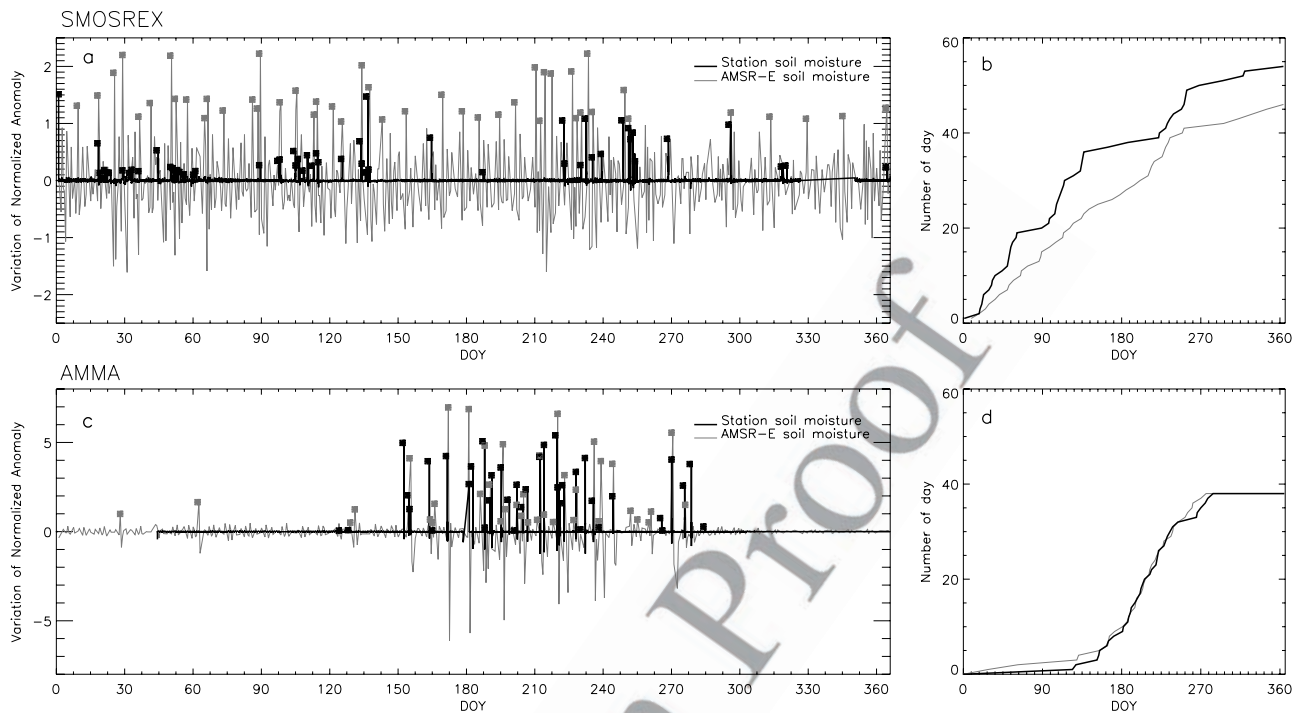


Figure 3. (left) Increments of standardized anomaly of SM from ground station (black) and AMSR-E product (grey), over (a) and (b) SMOSREX and (c) and (d) AMMA-Mali. Significant increments are indicated by a square. (right) Cumulated number days with significant positive increments.

216 divided by the standard deviation of the time series. Despite
 217 quite large noise, AMSR-E SM product provides good
 218 agreement with ground data in term of temporal variability.
 219 Table 3 indicates a significant correlation of 17.3% with an
 220 error risk at 0.001, which is a good result according to
 221 diversity of climate conditions. The AMSR-E performances
 222 vary with the seasons ranging from 2.1% in JFM, to 81.1%
 223 in AMJ. In JAS, SM and VWC decrease. Accordingly, their
 224 contribution to the microwaves signal are opposite. SM
 225 dynamics contributes to increase TB while vegetation
 226 dynamics leads to decrease TB. In OND, poor correlation
 227 are not due to frozen event occurrence. During this season,
 228 SM and VWC increase, leading again to opposite effect on
 229 TB dynamics. In this conditions, where seasonal trend of
 230 SM and VWC are correlated, SM retrieval is made very
 231 challenging and requires to account with accuracy for the
 232 vegetation effect on the signal [*de Rosnay et al., 2006*].
 233 These results show that the suitability of AMSR-E SM
 234 products to depict SM dynamics is depending on the season.
 235 [23] In contrast to SM products, PR at both 6.9 GHz and
 236 10.7 GHz are well correlated with the in-situ observations.
 237 At the annual scale correlation values are 60.4% and 61.4%
 238 at C and X-band, respectively. Results at the seasonal scale
 239 also indicate significant correlation values for any term of
 240 the year for both frequencies. The best agreement is
 241 provided by X-band measurements in spring time (AMJ),
 242 with a 78.9% correlation, as clearly shown in Figure 2c.
 243 This indicates the suitability of AMSR-E PR products to

capture normalized SM dynamics over this site at seasonal 244
 and annual scales. 245

[24] Figure 3a shows the ability of AMSR-E products to 246
 capture SM variations at the precipitation event scale. Based 247
 on normalized SM anomalies, a threshold is used to filter 248
 out signal noise and low SM increases from significant SM 249
 variations. Based on data monitored during dry period it is 250
 fixed to be 0.1 for ground measurements and 1.0 for 251
 AMSR-E SM products. Positive increments larger than 252
 the threshold, represented by squares on the figure, are 253
 related to relatively important precipitation occurrence. 254
 Figure 3b shows the cumulated number of days where 255
 positive SM increments is obtained, for both AMSR-E 256
 and ground measurements of SM. Ground measurements 257
 indicate 54 days with significant positive increments. 258
 According to field observation of precipitation, they corre- 259
 spond to precipitation events larger than 2 mm, which 260
 represent 90% of the annual rainfall. 261

4.2. AMMA-Mali 262

[25] Similar analysis is conducted for the AMMA-Mali 263
 site. AMSR-E product, which is overestimated, does not 264
 capture the correct range of SM (Figure 2 (bottom)). Bias on 265
 volumetric SM is 5.9% at the annual scale (Table 3). The 266
 lower bias is obtained during rainy season and the higher 267
 bias is obtained during dry season (4.7% in JAS and 7.7% 268
 in JFM). AMSR-E SM product presents a minimum SM 269
 threshold, which is inconsistently higher during the dry 270

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.

271 season (about 7%) than during then rainy season (about
272 5%). Despite of this, the annual cycle of AMSR-E volu-
273 metric SM product is shown to capture large SM increases
274 related to strong precipitation events occurring in the
275 monsoon season.

276 [26] Normalized values of SM are shown in Figure 2e.
277 Corresponding significant correlation is indicated in Table 3
278 to be 54.3%. Lower values of correlation are obtained in dry
279 season (24.6% in JFM) due to signal noise which is larger
280 than SM variations in this season. But significant correlation
281 values obtained in AMJ (62.9%), JAS (53.5%) and OND
282 (73.5%) are particularly noteworthy when SM dynamics is
283 more important. All of the correlation values are significant,
284 indicating that AMSR-E SM products is able to capture
285 efficiently the SM dynamics over this Sahelian site, at both
286 annual and seasonal scales.

287 [27] PR products are significantly correlated to ground
288 SM at the annual scale, with values of 59.3% and 44.6% for
289 C-band and X-band respectively. As for SM products, best
290 agreement between PR and ground SM are obtained during
291 the monsoon season, with correlation values of 66.7% at
292 C-band and 60.6% at X-band. Figure 2f confirms this good
293 agreement, showing normalized C-band PR and ground
294 SM.

295 [28] Figure 3c shows the evaluation of AMSR-E SM
296 products at the rainfall event scale. For this site, the
297 minimum threshold to consider increments of normalized
298 SM is determined based on dry season data to be 0.05 and
299 0.5 for ground station and AMSR-E SM product, respec-
300 tively. AMSR-E SM product indicate that 38 days of the
301 year present a positive increment, also detected by ground
302 measurements, which is consistent with precipitation data.
303 Moreover, a very good agreement concerning their temporal
304 distribution is shown by Figure 3d. Accordingly AMSR-E
305 SM product is shown to capture with a high degree of
306 accuracy the occurrence of SM increases at the precipitation
307 event scale over AMMA-Mali.

309 5. Conclusion

310 [29] This paper investigates the ability of AMSR-E
311 products provided by the NASA, to capture the ground
312 SM over two sites.

313 [30] For both sites AMSR-E SM products and polariza-
314 tion ratio are shown to be noisy, particularly at the daily
315 scale, and the absolutes values of SM are not captured
316 (Figures 2a and 2d). Ground measurements are underesti-
317 mated by AMSR-E SM product over the SMOSREX site
318 and overestimated over the AMMA-Mali site (Table 3). The
319 amplitude of volumetric SM provided AMSR-E products, is
320 shown to be underestimated over both sites. Nevertheless,
321 AMSR-E SM product captures the SM temporal variability
322 (Figures 2b and 2e).

323 [31] However, this paper shows that polarization ratios at
324 C and X-band are more suitable than SM product to capture
325 the SM dynamics over the two sites. Indeed, due to serious
326 contamination by RFI, multi-source information provided
327 by the different operating frequencies of AMSR-E is not
328 fully used in the NASA AMSR-E processing chain. In
329 particular, C-band data, which are highly relevant for SM
330 retrieval, are not used, limiting thereby the performances of
331 the algorithm.

[32] At the precipitation event scale, it is shown that 332
AMSR-E performs very well to detect occurrence of SM 333
variation over AMMA-Mali site, with a perfect agreement 334
of the timing as shown by the Figures 3c and 3d. This good 335
performance is particularly noteworthy and very promising 336
for the use of AMSR-E product in Sahelian area. 337

[33] The results presented in this paper clearly show that, 338
(1) the polarization ratio product is in better agreement with 339
ground measurements than SM products (2) ability of 340
AMSR-E to retrieve SM in the studied temperate areas 341
must be taken with care but temporal variability of surface 342
SM is captured by the PR, (3) AMSR-E is highly suitable 343
for SM remote sensing over semi-arid areas. It is shown to 344
capture the SM variability in term of normalized SM values, 345
at any temporal scale. 346

[34] The future SMOS sensor, with higher sensitivity to 347
SM due to L-band measurements, is expected to provide 348
improved accuracy in SM variability retrieval, as well as in 349
term of volumetric SM. 350

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