Mapping surface soil moisture over the Gourma mesoscale site (Mali) by using ENVISAT ASAR data.

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Response to the reviewers'#3 comments

<u>Major comments:</u>

1) As suggested by the reviewer, the SMEX and NAFE'05 campaigns have been presented in the introduction section to complete the list of the international campaigns conducted with the aim of on soil moisture estimation. The three relevant following references have been added to the paper:

- Panciera, R., Walker, J.P., Kalma, J.D., Kim, E.J., Hacker, J.M., Merlin, O., Berger, M., & Skou, N.:. The NAFE'05/CoSMOS data set: Toward SMOS Soil moisture retrieval, Downscaling, and Assimilation. IEEE Transaction on geoscience and remote sensing, 46, 736-745, 2008

- Mladenova, I., Lakshmi, V., Walker, J.P., Panciera, R., Wagner, W., & Doubkova, M.: Validation of the ASAR Global Monitoring Mode Soil Moisture Product Using the NAFE'O5 Data Set. IEEE Transaction on geoscience and remote sensing, 48, 2498-2508, 2010.

*- Jackson, T. J., R. Bindlish, A. J. Gasiewski***,** *B. B. Stankov***,** *M. Klein, E. G. Njoku, D. Bosch, T. L. Coleman, C. A. Laymon, and P. Starks, 2005: Polarimetric scanning radiometer C- and X-band microwave observations during SMEX03.* IEEE Trans. Geosci. Rem. Sen., *43, 2418-2430.*

The relevant work proposed by Mladenova et al., 2010 aims to use the ground dataset acquired during the NAFE campaign to validate the soil moisture product estimated with the ENVISAT/ASAR Global Monitoring mode. This paper shows that the GM mode can be used to retrieve soil moisture at low spatial resolution (R<0.75) as indicated in the following figure taken from the Mladenova's paper (figure 1a). This figure shows that a weak relationship is obtained at fine scale due to a noise levels present in the 1 km data. Some conclusions are observed in Pathe et al., 2009 with the comparison between ASAR GM derived - 3km SSM products versus *in situ* data (figure 1b). Statistical analyses of the correlation index indicate a median of about 0.5 with maximum and minimum values respectively equals to 0.8 and 0.2. A higher correlation coefficient is always obtained at lower spatial scale (25km). This behaviour is explained by the "high noise levels present in the 1 km data" (page 2504 of Mladenova et al., 2010).

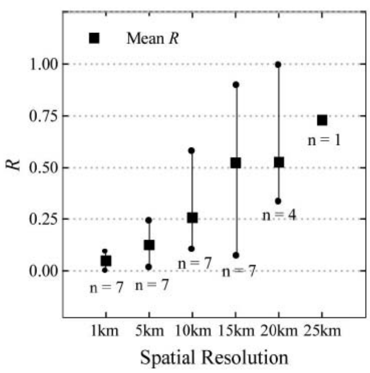


Fig. 4. Daily R-value variation with spatial resolution between ASAR GM SSM (m^3/m^3) and PLMR SM (m^3/m^3). Black solid squares show the average from paired days (n), whereas the upper and lower limits of the whiskers indicate, respectively, the minimum and maximum correlation coefficients at a particular spatial resolution.

a)

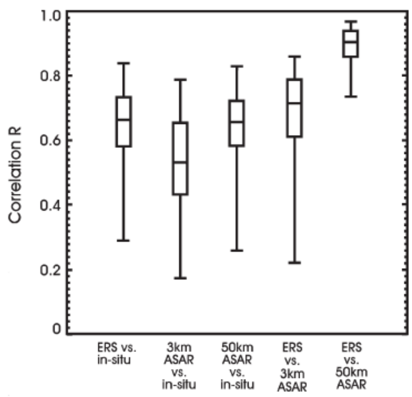


Fig. 7. Correlation (R) between four soil moisture data sets for 75 Oklahoma MESONET stations: ERS scatterometer versus *in situ*, 3-km ASAR GM versus *in situ*, 50-km ASAR GM versus *in situ*, ERS scatterometer versus 3-km ASAR GM, and ERS scatterometer versus 50-km ASAR GM.

b)

Figure 1: Correlation coefficient estimated between different soil moisture data sets. These results are respectively presented in Mladenova et al., 2010 (a) and in Pathe et al., 2009 (b).

This results from the performances of the ASAR GM mode (see the following table):

Parameter	Unit	IM Mode	WS Mode	GM Mode	ERS-1/2
Polarization		VV or HH	VV or HH	VV or HH	VV
Spatial resolution	m	27.5x28.1	149x145	949x977	27.5x28.1
Radiometric resolution	dB	1.54	1.45 to 1.72	1.35 to 1.44	2.07
Radiometric Accuracy (1 σ)	dB	0.39 to 0.46	0.40 to 0.48	0.51 to 0.58	n/a
Radiometric stability (1 σ)	dB	0.32 to 0.40	0.32 to 0.42	0.46 to 0.53	0.24/0.27
Noise equivalent σ_n^0	dB	-19.6 to -22.1	-20.9 to -26.2	-31.5 to -35.0	-26.2 to -25.2
Effective number of looks		~4	~13	~7	~3

Table I: Summary of ASAR and ERS performances (extracted from Baup et al., 2007b)

Comparisons between WS and GM radiometric resolutions also confirm the higher potential of WS mode for monitoring SSM at higher spatial resolution (figure 2).

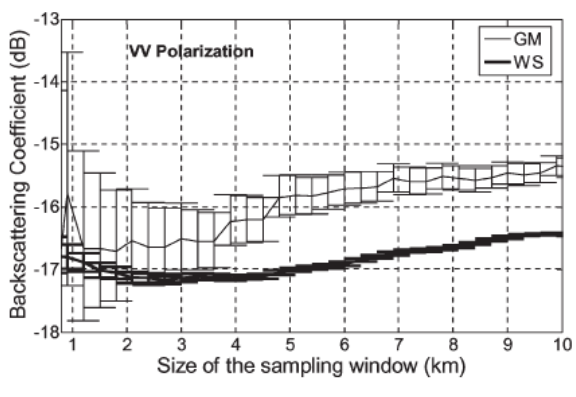


Fig. 2. Variation of the radiometric resolution versus the size of the sampling window for a GM image acquired on February 24, 2004 and a WS image acquired on January 16, 2005 (VV polarization). The angles of incidence are about 31° (GM) and 42° (WS), respectively.

Figure 2: Variation of the radiometric resolution versus the size of the sampling window for GM and WS mode (Baup et al., 2007b)

All these reasons show that is it still important to explore the Wide Swath (WS) mode capabilities for soil moisture mapping due to its high spatial coverage and its high radiometric specifications compared to the GM mode (ENL, radiometric accuracy and radiometric stability).

Pathe, C., Wagner, W., Sabel, D., Doubkova, M., & Basara, J.B.: Using ENVISAT ASAR Global Mode for surface soil moisture retrieval over Oklahoma, USA. IEEE Transaction on geoscience and remote sensing, 47, 468-480, 2009.

"What is the interest of now comparing point measurements?"
Currently, soil moisture measurement network is mainly composed of point measurements. The high resolution airborne soil moisture maps are rare, apart from a few international campaigns. No such campaign has been conducted over the Malian mesoscale site.
Global soil moisture products are thus evaluated by using only point measurements (as those proposed by using ASCAT, ERS wind scatterometer and SMOS data). So, it seems important to explore the potentialities of point measurements and their limits for soil moisture mapping over homogeneous or heterogeneous land cover.

2) The aims of the present study are:
- to generalize a recently proposed method for surface soil moisture monitoring in sandy soils (Baup et al., 2007) of the Sahel to soil erosion (gravelly and rocky) surfaces, . Both surfaces account for more than 90% of the considered region. We use data collected at a second sandy site and a rocky site in the same region in Mali.
- to generate SSM maps at meso-scale (1 x 3°) by using a soil map.
- to evaluate the validity of the generated soil moisture maps at meso-scale with relevant and available SSM products (Zribi et al., 2008) and rainfall maps (Bergès and Chopin, 2004).

These objectives have been clarified in the proposed paper in the introduction and conclusion sections. Novelties since the last publication have also been highlighted since the last publication.

3) We add the following sentences at the beginning of the section 2.2.
"The ground data section 2.2 is divided in 3 sub-sections:
- 2.2.1: Surface soil moisture measurements
- 2.2.2: Rainfall measurements
- 2.2.3: Soil map

To improve the clarity of the manuscript, the following sentence has been inserted at the beginning of this section:
"This section presents the available ground data collected in 2005 for the processing and the evaluation of the SSM maps. Three different datasets are described: Surface Soil Moisture (SSM), rainfall and soil types"

4) Despite some scientific papers have been published on soil moisture retrievals from radar data in the framework of the AMMA project, only a few data have been acquired over the considered region.

Our manuscript is focused on radar data acquired in “Wide Swath” mode over the Malian mesoscale site during the 2005 rainy season. In 2005, a lot of images are available during the dry season (from January to May/June and from October to December), and all the available images of the rainy season have been used. Since 2002, the number of available images has been insufficient to provide a monitoring of SSM during a complete season, except in 2005,. Only few data are available from 2006 to nowadays (on average 2 images per year during the wet season). It is thus impossible to capture the temporal cycle of *SSM* by using the available data set.

5) Soil moisture maps are processed from two different polarization states (HH and VV).
The Baup et al., 2007b’s paper, shows that the absolute difference of the backscattering responses of WS and GM modes between HH and VV rarely exceeds 1dB whatever the incidence angle is.
In Frison et al., 2010, results obtained with the “Alternative Polarization” mode also confirm these observations at high spatial resolution (figure 3). Despite the small bias of about 1dB, the behavior seems similar in HH and VV polarization.

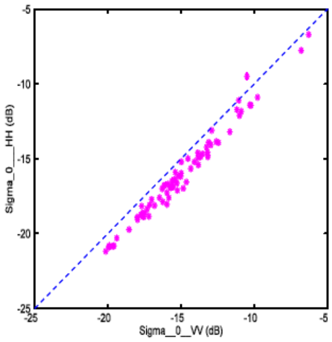


Figure 4 : Correlation between σ^0_{HH} and σ^0_{VV} over the Agoufou test site

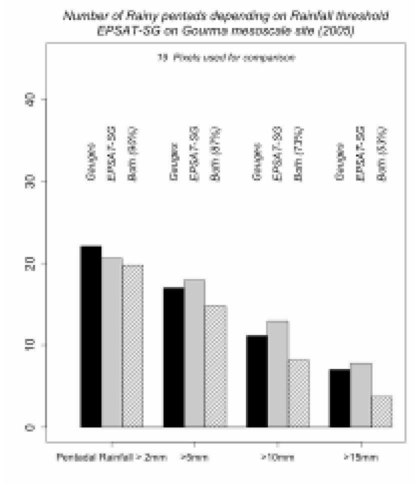
Figure 3 : Comparisons of backscattering coefficients acquired in HH and VV polarisation over the Agoufou sandy site (Frison et al., 2010).

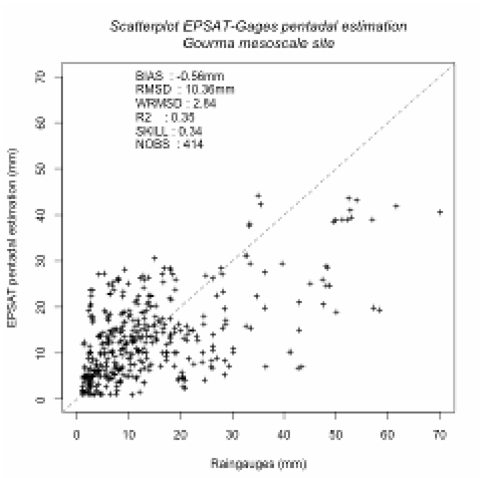
In the present paper, we compare only surface soil moisture products and not the backscattering signal. Vegetation effects which affect VV and HH responses are taken into account in the inversion processes of the two products (ASAR and WSC). So, no significant difference could be associated from the difference in polarization.

Frison. P.-L. Baup, F., Mougin, E., Faye, G., Hiernaux, P., Grippa, M., Rudant, J.-P.: Monitoring surface parameters over a sahelian region with ASAR alternate polarisation data. Proceeding of ESA Living planet conference, Bergen, 2010.

6) In 2005, only 5 automatic raingauges were installed in the Gourma AMMA mesoscale site. We also have access to long term precipitation records from 7 raingauge stations of the Malian meteorological service (DNM). We used these few and unevenly distributed measurements to produce by kriging daily maps of rainfall over the Gourma mesoscale site, with a spatial resolution of 10 km (see Lebel and Amani (1999) for a description of the kriging method). Comparisons have been made between EPSAT-SG and kriged rainfall estimates during the 2005 rainy season. Due to the low density of the network used for kriging, this comparison was limited to 19 gridpoints where the kriged rainfall are estimated accurately. As the rainfall probability is overestimated in the EPSAT-SG product, the number

of rainy days tends to increase to reduce the daily intensity as the monthly rain is equal to that given by GPCP products (Bergès et al., 2010). Raingauges measurements were compared to EPSAT-SG estimates on a five days basis over the Gourma mesoscale site. We first defined thresholds corresponding to low to maximum (greater than 0.1 mm), moderate to maximum (greater than 5 mm), high to maximum (greater than 10 mm) and very high (greater than 15 mm) rainfalls to compare the number of pentads with rainy days where *in situ* gauges and EPSAT-SG measured both a similar rainfall amount. A very good agreement is obtained especially for low rainfall, but the percentage of common detection decreases with the amount of rainfall. A relatively good agreement is obtained for pentadal rain lower than 20 mm whereas higher rainfalls are underestimated by EPSAT-SG. This explains why the statistical validation parameters exhibit average scores. Nevertheless, EPSAT pentadal rainfall estimates are sufficiently accurate for comparing rainfall and soil moisture patterns.





J. C. Bergès, I. Jobard, F. Chopin, and R. Roca. EPSAT-SG: a satellite method for precipitation estimation; its concepts and implementation for the AMMA experiment, Ann. Geophys., 28, 289-308, doi:10.5194/angeo-28-289,2010.

Lebel T. and A. Amani. Rainfall estimation in the Sahel : what is the ground truth? Journal of Applied Meteorology 38, pp. 555-567, 1999.

In the proposed paper, the following sentence has been added in the « EPSAT-SG data" section:
"Evaluation of EPSAT-SG products in 2005 over the mesoscale window shown the EPSAT pentadal rainfall estimates are sufficiently accurate for comparing rainfall and soil moisture patterns. A relatively good agreement is obtained for rain lower than 20 mm whereas higher rainfalls are underestimated by EPSAT-SG."

- Over this area, the grassland evapotranspiration commonly ranges between 1 and 3 mm day^{-1} and can reach 3–4 mm day^{-1} (Timouk et al., 2009).

F. Timouk, L. Kergoat, E. Mougin, C.R. Lloyd, E. Ceschia, J.-M. Cohard, P. de Rosnay, P. Hiernaux, V. Demarez, C.M. Taylor. Response of surface energy balance to water regime and vegetation development in a Sahelian landscape, Journal of Hydrology., 375(1-2), 178-189, doi:10.1016/j.jhydrol.2009.04.022, 2009.

The following sentence has been added at the end of the "study site description" section:

“Evapotranspiration over the grassland commonly ranges between 1 and 3 mm. day^{-1} and can reaches 3–4 mm.day^{-1} (Timouk et al., 2009).”

7) This NDVI threshold corresponds to the offset observed on the MODIS data acquired during the dry season over the sandy surfaces of the Malian mesoscale site (e.g. Mougin et al., 2009)

Mougin et al., 2009: Evaluation of MODIS LAI products in a Sahelian environment (Gourma, Mali), Poster presented at the 4h Global vegetation workshop, University of Montana, Missoula, June 16-19.

8) This sentence has been reformulated to take into account the precision of the EPSAT products (RMSD=10mm) and to underline the relation between the SSM and the total rainfall of the preceding days.

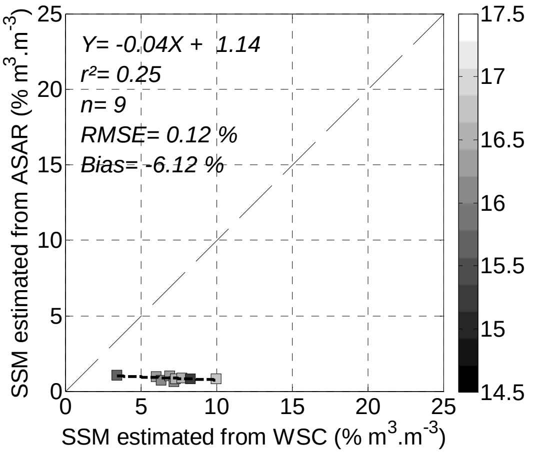
“Patches of high *SSM* to the North of Tin Tadeini can be related to the precipitations that fell during the previous 4 days totalling 10 to 12mm (Fig. 7). Rainfall occurred on the same day (a total of 2mm estimated from EPSAT-SG) should have a minor influence since this quantity is very small for such an arid area.”

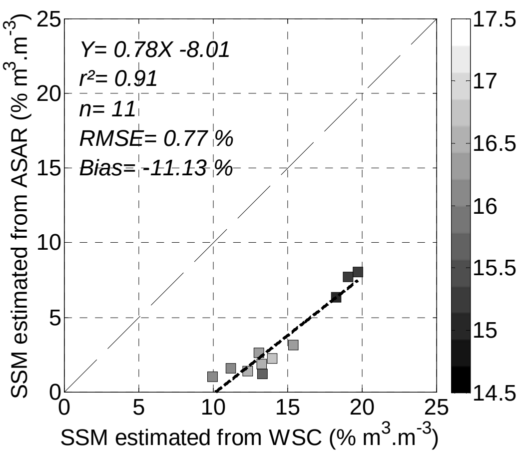
All the EPSAT-SG and WSC data have been taken as close as possible before the acquisition of the ASAR data to reduce uncertainties of analyses (especially to avoid the *SSM* variations due to rain events that occurred after the ASAR acquisition).

9) Yes, we want to show that the large scale spatial trends are well monitored by EPSAT-SG but the higher spatial variability of *SSM* is not observed using these data.
This sentence has been reformulated as follows:

“On August 4th (DoY 216), general large scale spatial trend of the *SSM* map shows an overall good agreement with the daily rainfall EPSAT-SG map, especially in the Northern part of the considered window (Fig. 8). Particularly, the *SSM* maps point out the high spatial heterogeneity of *SSM* due to fine scale rainfalls events that are not observed in the ESPSAT-SG data.”

10) Figures 11a and 11b have been modified and calculations have been made separately for the dry and wet season.





The important bias observed on these 2 figures (-6% and -11%) are consistent with results presented in Gruhier et al. (2010) over the same region of interest. For example, the 3 following figures, taken from Gruhier et al. (2010), represent the comparison between ERS/CETP *SSM* products (similar products are used in our study but not the same data) and ground soil moisture measured over three local tests sites.

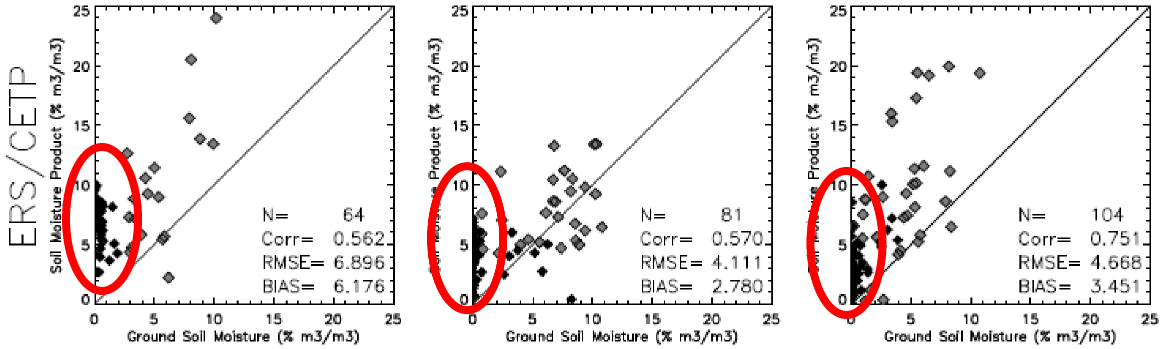


Fig. 11. Soil moisture from products versus from ground measurements. Black points correspond to dry seasons (October to June) and grey points to monsoon seasons (July-August-September). Statistical results shown are calculated during two years period.

Red circles indicate the high variability of estimated SSM for dry surfaces (as observed in our paper). These figures show the general overestimation of SSM by ERS/WSC *SSM* product.

The bias in the Mehrez et al's products originate from the method used to derive soil moisture. This method is based on the largest difference between maximum and minimum bascattering values that are observed in the temporal series. As minimum values in WSC data are not observed during the dry season but at the beginning of the rainy season (see e.g. Frison et al., 1996; Jarlan et al., 2002; Zine et al., 2005), SSM derived values are overestimated during the dry period.

Frison, P.L. and Mougin, E., 1996. Use of the ERS-1 Wind scatterometer data over land surfaces. IEEE Transaction on geoscience and remote sensing, No 2, 34: 550-560.

Jarlan, L., Mougin, E., Frison, P.L., Mazzega, P. and Hiernaux, P., 2002. Analysis of ERS wind scatterometter time series over Sahel (Mali). Remote Sensing of Environment, 81: 404-415.

Zine, S., Jarlan, L., Frison, P.L., Hiernaux, P. and Rudant, J.P., 2005. Land surface parameter monitoring with ERS scatterometer data over the Sahel: A comparison between agro-pastoral and pastoral areas. Remote Sensing of Environment, 96: 438-452.

Gruhier C., de Rosnay P., Hasenauer S., Holmes T., de Jeu R., Kerr Y., Mougin E., Njoku E., Timouk F.,Wagner W., and Zribi M. Soil moisture active and passive microwave products: intercomparison and evaluation over a Sahelian site, Hydrology and Earth System Science, 14, 141-156,2010.

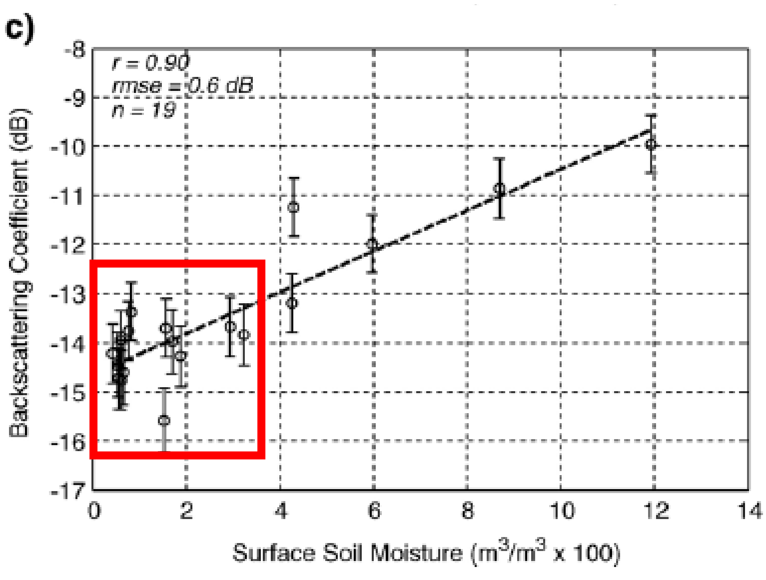
This sentence has been rephrased :
“WSC products show a strong agreement with ASAR products but with much higher *SSM* values estimated during the dry period as already observed by Gruhier et al., 2010 (between 14.5°N to 16.5°N).”

11) There are two possible explanations:

- Higher soil moisture values observed in the northern part of the image are mainly due to the presence of the Niger River and flooded vegetation.
- The noisy 0 to 10% *SSM* values observed from 14,5°N to 17°N is a general observation done all over the dry season (Gruhier et al., 2010).

The sentence has been rephrased to clarify comments concerning local and regional scales:
"In contrast, soil moisture patterns derived from WSC data are not in accordance with ASAR and EPSAT products. Indeed, despite no rainfall occurred during the 4 previous days before the radar acquisition (WSC and ASAR), only low resolution products indicate high surface soil moisture in the Northern part of the image. This phenomenon is locally attributed to the presence of the Niger River and to flooded vegetation which highly contribute to increase the backscattering coefficient. High resolution data allow masking this specific region and avoid overestimated *SSM values.*
Overall, the temporal variation of *SSM* values (0 to 10%) that can be observed from 14.5°N to 17°N is small during the entire dry season (Gruhier et al., 2010)."

12) The "noise" effect comes from the radar signal instability (±0.6dB for ENVISAT/ASAR) estimated in Baup et al., 2007 over this area at this spatial scale. This instability does not allow SSM to be estimated below 4% (m^3 / m^3) as shown on the following figure taken from Baup et al., 2007a. Points inside the red square do not present any correlation with surface soil moisture.



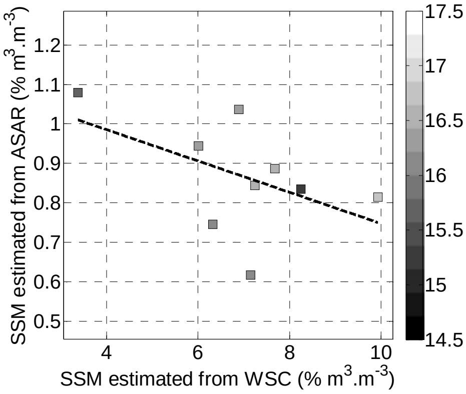
The sentence has been rephrased:
"The dry season distribution indicates that *SSM* values mainly range between 0 and 4% due to radar signal instability ((±0.6dB) during this period (Baup et al., 2007a; 2007b)."

13) To avoid confusion, the "noise and offset" terms have been removed from the text.

This sentence has been rewritten and one recent reference has been added.

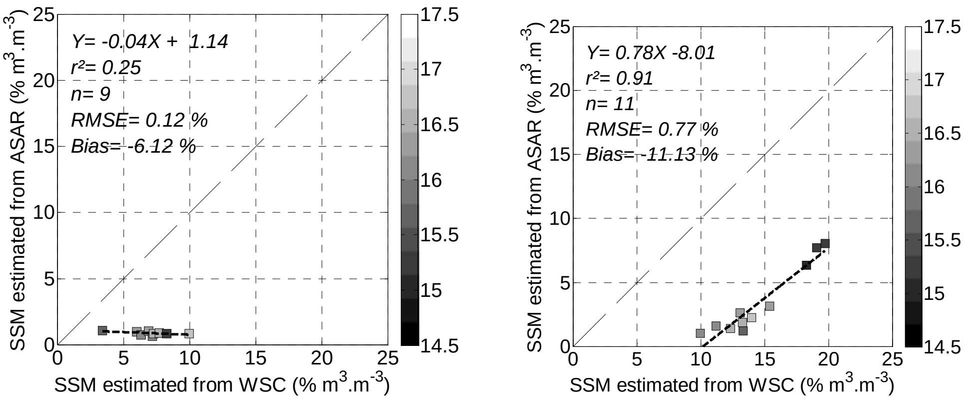
"Dry and wet periods are separated in the analysis to better discriminate between noise and changes related to SSM. During the dry season characterised by no rainfall event, WSC-derived *SSM*, ranging between 3% and 10%, is obviously overestimated, as already mentioned by Gruhier et al. (2010) (Fig. 12a). The observed bias of 6% between ASAR SSM and WSC SSM also confirms this overestimation. The highest *SSM* values are located in the Northern part of the site where the WSC signal is mainly affected by the Niger River and its vegetation. The initial offset of 3% is explained by the inversion method initially developed over slightly wetter surfaces (see Zribi et al., 2008). In contrast, ASAR-derived *SSM* show a higher stability with only 2% of dynamic range and an offset of about 1%."

14) A local focus on figure 11a (see below) shows that all the points are not located along on a straight line. This explains the low correlation coefficient and low rmse values. It is also important to notice the high stability of ASAR SSM values found during the dry season with only 0.5% of variability at 25km scale.



Figures 11a and 11b have been modified and show the same axis scale.

Bias and rmse statistical parameters have been added on Figures 11a and b.



15) These two dates have been chosen since they are much contrasted and representative of soil moisture heterogeneity of the area over the rainy season.

The best year for evaluating the WS mode over the Malian mesoscale window is 2005 with 5 images acquired during the rainy season. Excepted in 2005, no consistent data set is available. Only few data are available from 2006 to nowadays (on average only 2 images per year are acquired during the wet season). It is thus impossible to capture the temporal cycle of *SSM* by this way.

The interesting paper that is mentioned deals with the temporal stability of soil moisture and ASAR radar backscatter (Wagner et al., 2008). In this paper, the authors deal with 72 ASAR images acquired in the WS mode over a study site located in Spain, where 20 sensors acquire continually the surface soil moisture. We can not apply the same approach in our context since only a few images and ground data are available. Nevertheless, the temporal stability of the backscattering coefficient has been studied over our area during two successive dry seasons (Baup et al., 2007b). Results indicate that the WS mode shows a standard deviation of 0.32dB for dry soil moisture patterns against 0.55dB for the GM mode for the same surface conditions.

The reference to Wagner et al. (2008) paper has been added in the introduction section.

16) These two points have been reformulated with reference to your previous comments number 10, 11 and 13.

17) In Zribi et al., 2008, *SSM* values are expressed in volumetric percentage (% $m^3.m^{-3}$) in contrast to others studies where *SSM* derived from WSC data are generally given between 0 and 100% (the maximum value being associated to a saturated soil). This is the reason why we can directly compare ASAR SSM and WSC SSM absolutes values.

The figure given below presents an example of *SSM* temporal variation of WSC SSM products, estimated over Sahelian and desert regions (Zribi et al., 2008). This figure shows that all surface soil moistures are expressed in % $m^3.m^{-3}$.

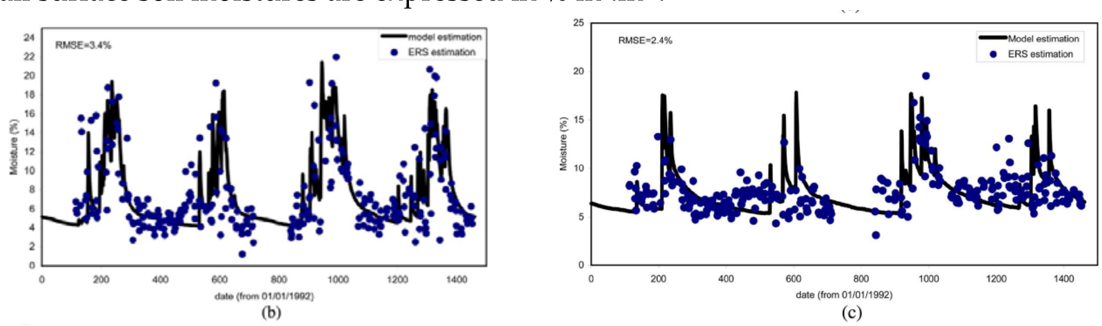


Fig. 7. Comparison between GSWP-2 model outputs and our soil moisture estimations for three regions. (a) Tropical region (10°–3°). (b) Sahel region (13°–3°). (c) Desert region (16°–3°).

18) The aims of the present study are:
- to generalize a recently proposed method for surface soil moisture monitoring in sandy soils (Baup et al., 2007) of the Sahel to soil erosion (gravely and rocky) surfaces. Both surfaces account for more than 90% of the considered region. We use data collected at a second sandy site and a rocky site in the same region in Mali.
- to generate SSM maps at meso-scale (1 x 3°) by using a soil map.
- to evaluate the validity of the generated soil moisture maps at meso-scale with relevant and available SSM products (Zribi et al., 2008) and rainfall maps (Bergès and Chopin, 2004).

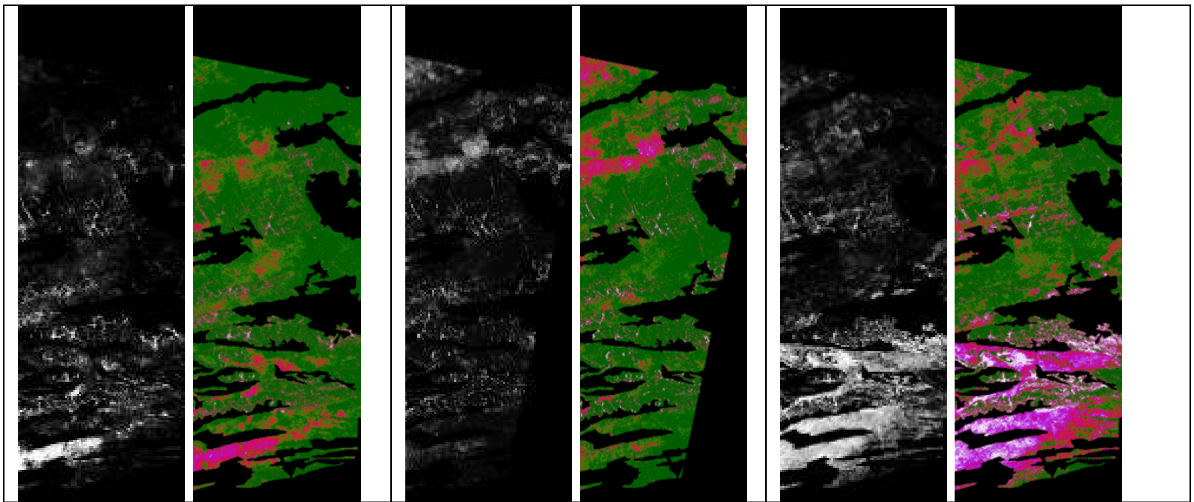
These objectives have been clarified in the proposed paper in the introduction and conclusion sections. Novelties since the last publication have also been highlighted since the last publication.

Editorial comments:

- Following the reviewer suggestion, the modification has been done.
- The unit of LAI has been added "(Leaf Area Index –LAI- <2m^2.m^{-2})"
- Modification done.
- The calibration results presented by de Rosnay et al., 2009 are referenced. The sentence has been reformulated as follows:

"In this study, *SSM* is expressed in volumetric water content (m^3 / m^3) in accordance with the calibration method presented in de Rosnay et al., 2009"

- Modification done.
- Modification done.
- Modification done.
- "Established" has been replaced by "produced"
- Modification done.
- Modification done.
- Modification done.
- We use a specific color map to improve the contrast between SSM values. The grey color map does not underline contrasted areas as well as the proposed color map (see figure below for comparisons). Moreover, masked areas are not well visible by using grey color map.



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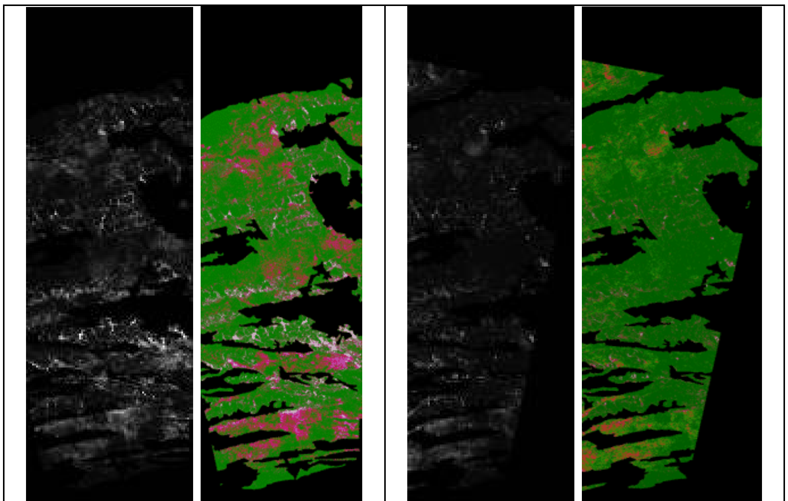

2005-09-03 | 2005-09-08

- Modification done.