SURFACE SOIL MOISTURE MAPPING OVER WEST AFRICA USING INFRARED MEASUREMENTS FROM METEOSAT GEOSTATIONARY SATELLITE: COMPARISION OF ALGORITHMES

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ABSTRACT

In this study, surface soil moisture (SSM) over West Africa was retrieved from land surface temperature (LST) based on thermal infrared data provided by the geostationary Meteosat 8 satellite. Several authors proposed various algorithms to retrieve SSM from LST product but, to our knowledge, no study was devoted to compare different methodologies over a same domain using satellite LST measurements as well as in-situ measurements. At this time, the paper presents three different methodologies. The first one was based on the linear relationship observed between LST and SSM. The second one was based on early morning surface temperature gradients, and the third one was based on LST anomalies. A systematic analysis of errors was carried out at the locale scale using in-situ soil moisture and soil temperature measurements. A second step will be devoted to evaluate SSM maps at the regional scale using microwave measurement provided by the Advanced Microwave Scanning Radiometer (AMSR-E) daily microwave measurements.

1. INTRODUCTION

Determining soil moisture content over large areas with a suitable spatial and temporal resolution is an important issue for hydrological and meteorological applications. Since several years, there have been many efforts to develop remote sensing techniques mainly based on microwave measurements. However, due to large wavelengths, only polar orbit satellites can provide microwave measurements. It follows that existing soil moisture satellite estimations can be either characterized by a good spatial resolution associated with a poor temporal resolution (such ENVISAT-ASAR, ERS-SAR) or a good temporal resolution associated with a poor spatial resolution (such AMSR-E, Metop-ASCAT). To solve this problem, several authors proposed to use remote thermal infrared measurements of the land surface to provide soil moisture estimates (Gillies and Carlson 1995; Rabin and Schmit 2006; Wetzel et al. 1984) . As thermal infrared measurements are available from geostationary satellites, a quite good spatial resolution (3 to 5 km depending on the latitude) and temporal resolution (15 to 30 minutes) measurements can be obtained. Nevertheless, to our knowledge, no study was devoted to compare various methodologies to estimate surface soil moisture based on thermal infrared measurements over a same region. The objective of this study was to evaluate three different methodologies for providing soil moisture estimates based on land surface temperatures. The region of interest was the sahelian region (9°N to 20°N) in West Africa which is an ideal region due to a significant land surface temperature diurnal cycle and a weak vegetation cover. In the first part of the paper, in-situ land surface temperatures were used and soil moisture estimates were compared to in-situ soil moisture measurements whereas in the second part, satellite land surface temperatures were used and assessed at the locale scale.

2. DATA AND METHODS

2.1 Studied area

The studied area is a 5.760.000 km² region located in West Africa (9°N to 20°N; 20°W to 20°E). The annual rainfall ranges from about 1300 mm in the South to close to 0 mm in the North. There is a strong meridian gradient of vegetation with trees, crops and grasslands in the south whereas only semi-arid vegetation and desert in the north of the domain. Rainfall starts in June and lasts until the end of September with a maximum in August.

Three sites have been instrumented with soil moisture and soil temperature probes during the AMMA project (African Monsoon Multidisciplinary Analysis) over three different climate areas. The first one is located in Niger (Wankama site, 13.6°N, 2.6°E). The second one is located in Mali (Agoufou site, 15.3°N, 1.3°W) and the last one is located in Benin (Nalohou site, 9.6°N, 2.3°W).

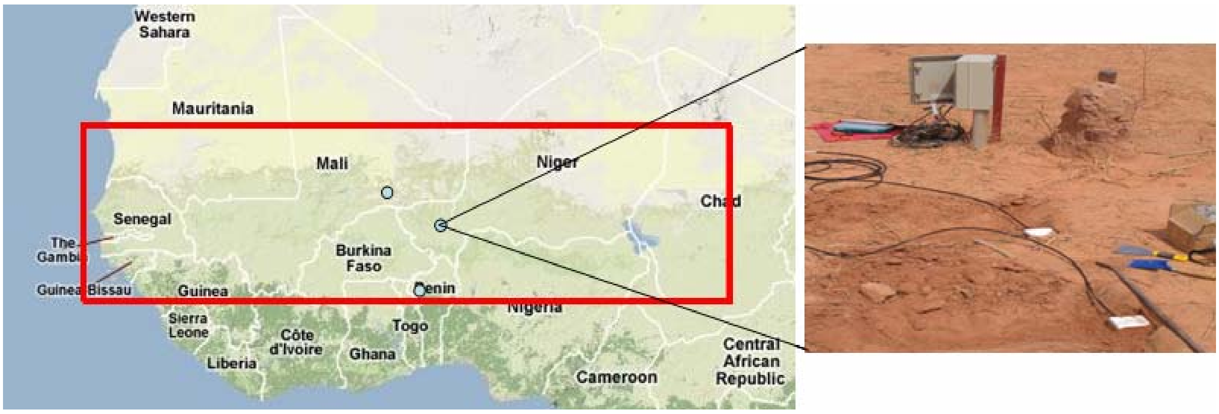

Figure 1. Studied area in West Africa (9°N-20°N; 20°W-20°E), location of the three sites in Benin, Niger and Mali and view of two (of the six) near surface soil moisture probes (CS616 Campbell Scientific) in Niger.

2.2 Datasets

2.2.1 Soil moisture and land surface temperature in-situ measurements

The local stations are equipped with two-wire Time Domain Reflectometry (TDR) probes measuring 265 mm in length and installed at 5 cm depths in the soil. On each site, 3 to 6 soil moisture probes were installed in order to avoid local scale influence. In addition, soil temperature probes were installed at 5 cm depth over the Niger and Mali sites and at 10 cm depth over the Benin site. These stations recorded soil temperature and soil moisture every 15 min during all the 2006 rainy season except for the Niger site where soil moisture probes were installed on June 21st.

2.2.2 Satellite land surface temperature from Meteosat Second Generation (MSG)

Land surface temperature (LST) data were produced operationally by the LandSAF from SEVIRI observations onboard the MSG satellite (Wan and Dozier 1996). The spatial resolution of LST product is 5 by 5 km² and the temporal resolution is 15 minutes. A quantitative comparison was done to compare Meteosat LST with in-situ LST over the three sites. Results are presented in figure 2 and coefficients of determination are equal to 0.61, 0.68 and 0.63 for the Niger, the Benin and the Mali site respectively.

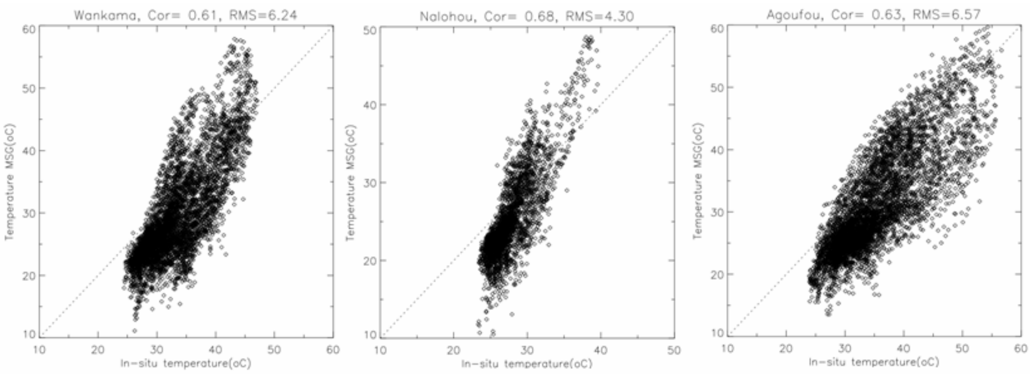

Figure 2. Scatterplots for June - September 2006 at the three sites: Wankama (Niger), Agoufou (Mali) and Nalohou (Benin).

2.3 LST to SSM: three methodologies

In this study, we investigated three different algorithms for estimating daily SSM retrievals from land surface temperatures (LST) over the three sites located in Niger, Mali and Benin.

The first methodology is based on the observed linear relationship between LST at a given time of the day and the corresponding SSM. (Wetzel et al. 1984) have shown that the mid-morning surface temperature with respect to solar radiation is optimally sensitive to soil moisture. Figure 3 shows an illustration of the relationship between in-situ LST at 0900 and in-situ SSM at 0900 over the Niger site during September 2006. The linear relationship is expressed as :

$$SSM_{0900} = a_0 + a_1.LST_{0900} \quad (1)$$

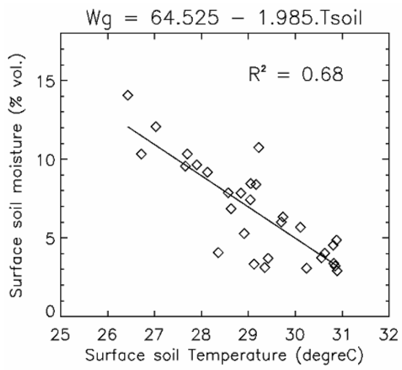

Figure 3. Observed linear relationship between land surface temperature at 0900 and surface soil moisture for September 2006 over the Niger site.

The strategy of the second methodology is to estimate an early morning temperature gradient (T_G) between 0800 and 1000 on every pixel by linear regression through the nine data points. This method was firstly evaluated by Wetzel et al. (1984) and was recently applied over South Africa by Pegram et al. (personal communication). This methodology assumes that there is an inverse linear relationship between SSM and surface temperature gradient T_G. In other word, T_G is expected to be weak for wet soils and large for dry soils.

The third methodology was initially proposed by Taylor et al. (2007) and was based on a linear relationship between LST anomalies and SSM. A long-term mean value of LST is calculated during the 21 previous days and compared to the LST at the current date. Negative LSTA are expected for wet soils and positive LSTA are expected for dry soils. LSTA at a given date t_{10} is calculated as:

$$LSTA_{0900}^{t_{21}} = LST_{0900}^{t_{21}} - \frac{1}{10}\sum_{k=t_0,t_{20}} LST_{0900}^{k} \quad (2)$$

It can be noted that the first methodology needs to determine regression coefficients and lead to directly provide SSM estimates whereas methodologies 2 and 3 only provide an indirect measurement of SSM. Following (Reichle and Koster 2005), daily SSM estimates are rescaled into volumetric soil moisture retrievals (% vol.) following:

$$SSM_{norm}^{t} = (X^{t} - \mu^{X}).\frac{\sigma^{SSM}}{\sigma^{X}} + \mu^{SSM} \quad (3)$$

to match the observed SSM and ensure that rescaled retrievals possess a long-term mean (μ) and standard deviation (σ) matching those derived from the soil moisture measurements for the same pixel. Soil moisture retrieval mean (μ^X) and standard deviation (σ^X) estimates are obtained by sampling a long-term time series of indirect estimates (SSM_1, T_G, LSTA or SSM_4). Likewise, the SSM mean (μ^{SSM}) and standard deviation (σ^{SSM}) are sampled from in situ SSM measurements over the three sites.

3. RESULTS AND DISCUSSION

3.1 In-situ measurements

The first part of the study focuses on the relationship between LST and SSM obtained at the local scale with in-situ soil moisture and soil temperature probes. The three methodologies are assessed by using the coefficient of determination (R^2, hereafter called the correlation) and the root mean square error (RMS). Results for the three sites and the three methodologies are presented in Table 1. Figure 4 presents the performances of the three methodologies over the Niger site. The grey area on Fig. 4 represents the maximum and the minimum values of the six surface soil moisture measurements of the Niger site (all sensors are belonging to a 5 by 5 km² area around the Wankama site in Niger). The correlation is calculated using the averaged value of the six independent soil moisture measurements.

It can be observed that the first methodology provides the best soil moisture estimates with a correlation that reach 0.69 and a RMS error equal to 2.0 % vol. Conversely, the second and third methodologies seem to be less accurate with R^2 that does not reach 0.4 and RMS error close to 4% vol. An explanation of the second methodology behaviour is related to the effect of vegetation which development is maximal from mid-august to end September. During this period, high values of SSM estimates correspond to low values of temperature gradients. The vegetation cover leads to decrease the diurnal soil temperature cycle and consequently decrease the early morning temperature gradient.

Regarding the Nalohou site (Benin), the first methodology yields to the better match the observations with R^2 equal to 0.63 and a weak RMS equal to 2.4 % vol. On the other hand, the second methodology produces slightly best score than the third one. The two last methodologies lead to poor R^2 and rather large RMS (> 4% vol.).

Finally, regarding the Agoufou site (Mali), the first and the second methodologies provide similar result with R^2 equal to about 0.4 and RMS error close to 4 % vol. It can be also noted that the temperature gradient methodology provide the best soil moisture estimation over the Mali site.

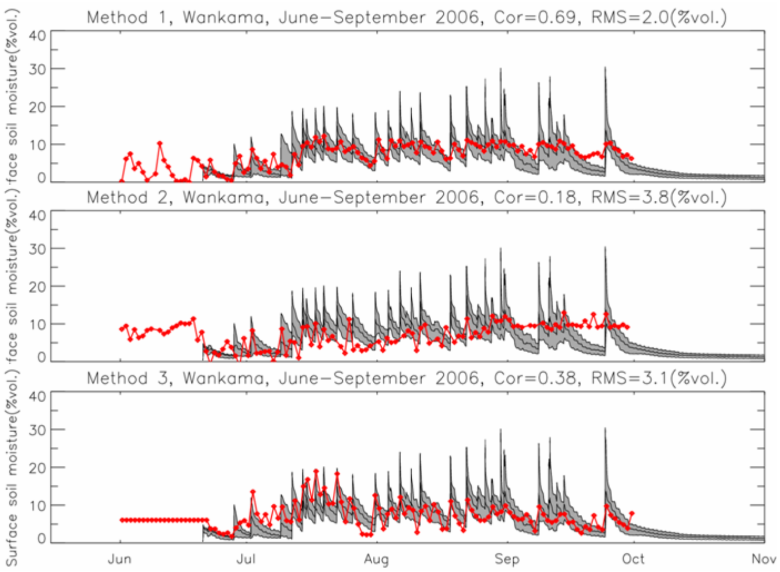

Figure 4. Illustration of the three methodologies over the Niger site

Table 1. Coefficient of determination (R^2) and root mean square error (RMS) of the 3 soil moisture methodologies applied over the 3 sites in Niger (Wankama), Mali (Agoufou) and Benin (Nalohou). Land surface temperatures are provided by in-situ soil temperature probes.

In-situ LST	Method 1		Method 2		Method 3	
	R^2	RMS (% vol.)	R^2	RMS (% vol.)	R^2	RMS (% vol.)
Wankama	0.69	2.0	0.18	3.8	0.38	3.1
Nalohou	0.63	2.4	0.17	4.1	0.10	4.5
Agoufou	0.46	2.9	0.36	3.1	0.19	3.6

3.2 Satellite measurements

In the last part of the study, land surface temperatures derived from Meteosat SEVIRI sensor were used to assess the three methodologies. Scores obtained over the three local sites are presented in Table 2. As expected, it can be observed that the accuracy of soil moisture estimates based on satellite LST measurement is weaker than that obtained using in-situ LST measurements. The first methodology remains the best one over the three sites. On the other hand, the second methodology provide the worst results with R^2 coefficients close to 0 and RMS error ranging from 4.1 to 5.5 % vol.

Table 2. Coefficient of determination (R^2) and root mean square error (RMS) of the 3 soil moisture methodologies applied over the 3 sites in Niger (Wankama), Mali (Agoufou) and Benin (Nalohou). Land surface temperatures are provided by satellite soil temperature estimates.

Satellite LST	Method 1		Method 2		Method 3	
	R^2	RMS (% vol.)	R^2	RMS (% vol.)	R^2	RMS (% vol.)
Wankama	0.32	3.0	0.06	4.1	0.14	3.7
Nalohou	0.51	3.1	0.01	5.5	0.22	3.1
Agoufou	0.15	4.0	0.01	5.1	0.09	4.3

4. CONCLUSIONS AND FUTURE WORKS

This study was a first attempt to evaluate various soil moisture estimates based on land surface temperature provided by in-situ or satellite measurements. The study at the locale scale pointed out the effect of uncertainties on the LST measurements on the soil moisture estimations. It was also shown that soil moisture estimates can be quite different from one methodology to another despite the same original information.

We are currently testing the three methodologies over the whole domain shown in Fig. 1. An overview of the obtained soil moisture estimates using three methodologies is presented in Fig. 5. The main difficulty of the study at the regional scale will be to find a reference soil moisture map in order to analyse agreements and disagreements between the three methodologies.

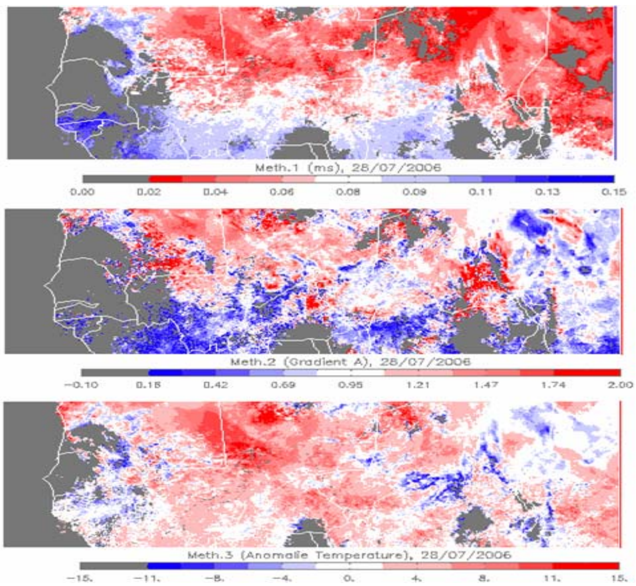

Figure 5. Regional soil moisture estimates using the three methodologies for the 28/07/2006 date.

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