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Estimating the Root-Zone Soil Moisture from the Combined Use of Time Series of Surface Soil Moisture and SVAT Modelling

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Abstract. This work investigates the possibility to retrieve the root-zone soil moisture from the combined use of time series of surface soil moisture, that can be estimated from microwave remote sensing instruments, and Soil-Vegetation-Atmosphere-Transfer (SVAT) modeling. The analysis is based on the ISBA surface scheme and two data sets acquired over soybean crops, in 1989 and 1990. They include very detailed measurements of soil and vegetation characteristics, mass and energy transfers in the soil-plant-atmosphere system and crop remote sensing signatures in the thermal and microwave domains during a 2- or 3-month period. The 3-month experiment in 1989, made it possible to investigate the accuracy of the soil reservoir retrievals, as a function of the time period and repetitivity of the surface measurements included in the retrieval process. This work contributes to a better definition of the requirements for the use of remotely-sensed microwave observations of surface soil moisture. This is a crucial problem, if we consider the increasing potential of microwave remote sensing technology and the fundamental needs in atmospheric and hydrological models for water transfer characterization in soil.

1 Introduction

This work investigates the possibility to estimate the root-zone soil moisture, from the combined use of surface soil moisture data and Soil-Vegetation-Atmosphere-Transfer (SVAT) modeling. The study contributes to the analysis of the potential interest of repetitive surface soil moisture estimations, which could be made with a 1-, 5-day temporal repetition, from spaceborne remote sensing (RS) intruments. Indeed, the analysis of the information content of time series of surface soil moisture estimates, over a 10-, 30-day period, is an important issue which could strongly contributes to support the development of spaceborne microwave remote sensing sensors. Previous research has shown that current technology has now the potential to develop passive or active microwave remote sensing systems which can provide information on surface soil moisture (Schmugge and Jackson, 1994; Jackson et al., 1995; Wigneron et al., 1995, 1996).

Several recent works have investigated the possibility to assess the hydrological conditions at depth (in the top 1- or 2-m soil layer) from the combined use of surface variables and SVAT modeling (Entekhabi et al., 1994; Ragab, 1995, Calvet et al., 1998). For instance, the feasibility of using brightness temperature measurements (microwave and infrared channels) to solve the inverse problem associated with soil moisture and heat profile was demonstrated by Entekhabi et al. (1994). This theoretical analysis was based on a Kalman filter using radiative transfer and coupled moisture and heat diffusion equations. Similarly, retrieval of the root-zone soil moisture was carried out by Calvet et al. (1998) using a continuous series of micrometeorological data measured on a fallow site in 1995-1996 (MUREX experiment). The study was based on the surface scheme ISBA (Noilhan and Planton, 1989), which is used in the operational simulations of the French weather forecast model ARPEGE. The root-zone soil moisture (w_2) was retrieved during a 15-day period from assimilation of ground measurements of surface soil moisture or surface temperature. It was found that one measurement of the [0-5cm] surface soil moisture every 3-4 days during the 15-day period, was sufficient to obtain good estimates of w_2 (Calvet et al., 1998).

The very satisfying results of the latter study were obtained for a rather short period of time and they had to be confirmed by works on other data sets. Also, some questions have to be adressed to prepare future spaceborne RS instruments. For instance, using longer period of time, it

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is important to investigate the sensitivity of the retrieval process on the time repetitivity and the integration period of the surface data. The present work investigates these aspects based on two data sets acquired during the vegetation cycle of soybean crops, in Avignon.

The data sets include detailed measurements of the soil and vegation characteristics, and of the energy and mass transfers of the soil/vegetation/atmosphere continuum. In order to account for the strong vertical profile of the soil characteristics between the surface and the root-zone, the approach proposed by Calvet et al. (1998) is modified. To compute the cost function, which quantifies the error between simulated and observed data in the retrieval process, the surface soil moisture data are normalized using the soil moisture at field capacity w_{FC} and at wilting point w_{WILT}.

2 Data set

The two data sets used in this work, were acquired during the vegetation cycle of a soybean crop, by two different teams of the INRA (Institut National de la Recherche Agronomique) Research Center in Avignon: the Soil Science Unit in 1989 (Bertuzzi et al., 1992) and the Bioclimatology Unit in 1990 (Olioso et al., 1996). The two crops were grown on the same site, a silty clay loam experimental field, from the beginning of July to the end of October in 1989 and to the end of September in 1990. The data set period comprises [DoY 200 - DoY 278] in 1989 and [DoY 209 - DoY 258] in 1990.

The crops received 233 mm in 1989, and 123 mm in 1990, of water from both rainfall and irrigation. The data sets include continuous measurements of the soil and vegetation characteristics, and of the energy and mass transfers from classical meteorological observations combined with surface and water budget measurements. During both experiments, incident radiation, wind speed, air temperature and vapour pressure were recorded above the canopy. Energy balance was monitored using various sets of intruments and evapotranspiration flux LE was derived from measurements of the net radiation Rn, the ground heat flux Gs and the sensible heat flux H (all terms are expressed in W/m^2) with bowen ratio and eddy correlation methods.

The vegetation characteristics were monitored throughout the crop cycle (in terms of wet and dry biomass (kg/m^2), Leaf Area Index LAI, crop height H_C (m), leaf angle distribution, canopy structure, ...). Thermal infrared brightness temperatures were continuously measured using radiometers (8-14 μm) in vertical viewing. In 1989, radar data were acquired by a scatterometer designed by CNES at 5.3 GHz, at incidence angles of 15 and 23°. Both thermal and radar RS observations were acquired throughout the crop cycle.

Water content profiles of soil, from 20 cm to about 1.6 m at depth, were recorded every day in 1989 and on a 2- or 3-day basis in 1990 with neutron probes (the vertical sampling interval was 10 cm). These water content profiles were performed to get the water storage variations of the root-zone reservoir, with a good temporal resolution. At the soil surface, accurate moisture profiles were obtained daily in 1989, at about 8.00 H (TU), in the top 20-cm soil layer from gravimetric measurements (at 0-1, 1-2, ... 7-10, 10-15 and 15-20 cm). In 1990, only the top 0-5 cm or 0-10cm and 10-20 cm soil layers were sampled at the same time (8.00 H TU), on 1- or 2-day basis. Soil moisture characterization was therefore more exhaustive in 1989.

An estimate of the soil moisture at field capacity w_{FC} and at wilting point w_{WILT} could be obtained from the soil water potential / gravimetric water content relationships computed by Chanzy (1991) over two layers [0-20 cm] and [20-80 cm]. An estimate of the soil moisture at field capacity is computed for a soil water potential ψ_S = -0.033 MPa, and that at wilting point for ψ_S = -1.5 MPa. If we consider the range of variations of the dry bulk density ρ_b (g/cm^3), the possible range of variations of w_{FC} (m^3/m^3) and w_{WILT} (m^3/m^3) are given in Table 1. The latter values are only qualitative, since the chosen values for ψ_S are indicative, for but they provide a useful range of variations of w_{FC} and w_{WILT} over the 0-80 cm vertical soil profile.

From field observations, the soil moisture at field capacity w_{FC} is usually set equal to 0.31 m^3/m^3, which corresponds to the higher values of w_{FC} given in Table1.

3 Method

3.1 The ISBA model

The land surface scheme ISBA (Interactions between Soil Biosphere Atmosphere), was developed by Météo-France and described by Noilhan and Planton (1989). It has been widely validated over vegetated and bare ground surfaces (Mahfouf and Noilhan, 1991; Noilhan and Mahfouf, 1995; Calvet et al., 1998, etc.). It is based on the equations of the force-restore method, initially applied by Bhumralkar (1975) to compute ground surface temperature in an atmospheric general circulation model. Deardorff (1977, 1978) developed a similar parameterization to compute the ground-surface moisture content over bare soils and vegetated surfaces. The ISBA scheme is used in this work as it is a simple model, with few input parameters, which can be easily coupled with remotely-sensed observations of the surface variables for assimilation and retrieval processes. The ISBA model predicts the time variations of five prognostic variables: the surface temperature T_s, the soil temperature T_2 at depth, the surface volumetric water content w_G, the mean volumetric water content of the soil reservoir w_2, and the amount of an interception reservoir W_r. Since a detailed description of the ISBA scheme can be found in several works (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1995), only a brief description of the water transfers is given in this section.

The simple water budget for w_G and w_2, derived from the force-restore method can be written as:

$$\delta w_G/\delta t = C_1/(\rho_w d_1)\ (P_G - E_G) - C_2/\tau_1\ (w_G - w_2),\quad 0 \leq w_G \leq w_{SAT} \qquad (1)$$

$$\delta w_2/\delta t = 1/(\rho_w d_2)\ (P_G - E_G - E_{TR}) - C_3/\tau_1 \max[0, (w_2 - w_{SAT})],\quad 0 \leq w_2 \leq w_{SAT} \qquad (2)$$

The first term on the right of Eq.(1) represents the influence of surface atmospheric fluxes (outputs due to soil evaporation E_G and inputs due to precipitation & irrigation P_G). The second term in Eq.(1) characterizes the diffusivity of water in the soil which tends to restore w_G toward the bulk value (w_2). The dimensionless coefficients C_1 and C_2 are highly dependent upon soil moisture (w_G and w_2) and soil texture. They can be calibrated from measurements or estimated using parameterizations derived from numerical experiments (Noilhan and Planton, 1989). The water budget for the mean volumetric water content w_2 (Eq.(2)) is similar and it is computed as a function of P_G, E_G, the transpiration rate E_{TR} and gravitational drainage, parameterized by the dimensionless coefficient C_3. The soil water reservoir R_2 (mm), can be directly related to the mean soil moisture w_2 (m^3/m^3) and to root depth d_2 (m):

$$R_2 = 1000\ (w_2 \cdot d_2) \qquad (3)$$

Equation (1) relates the time variations of surface soil moisture w_G to the variables of interest E_G and w_2. Therefore, if correct estimates of P_G can be obtained from the ground meterorological network, periodic observations of w_G will provide information on soil evaporation E_G and on the root-zone water content w_2. The retrieval process of w_2, performed in this work from temporal information on w_G, is based on this hypothesis.

The two soil parameters: w_{WILT} and w_{FC} are basic soil parameters, which are used to normalize the soil moisture content w_G and w_2, in the parameterizations of the water fluxes. In the following, the soil moisture data w (m^3/m^3) are normalized using w_{WILT} and w_{FC} to compute a soil moisture index Smi, which is given by:

$$\text{Smi} = (w - w_{WILT}) / (w_{FC} - w_{WILT}) \qquad (4)$$

However, as discussed in the previous section, there are strong vertical gradients of the soil texture and structure characteristics. Therefore, in this work, we distinguish the values for the "model" and the "observation" soil parameters w_{FC} and w_{WILT}. The "model" parameters are the ISBA input parameters. They are effective parameters which are considered to be representative of the whole soil layer (from surface to soil depth d_2) and which are used in Eq.(8) and Eq.(9). Conversely, the "observation" parameters in Table 2 correspond to the top layer of the soil surface, roughly the [0-5cm] top soil layer, which is the sampling depth of low frequency microwave RS observations. Eq.(4) is applied to surface soil moisture w_G: the simulated and the measured values of w_G are normalized using "model" and "observation" values of w_{WILT} and w_{FC}, respectively:

$$\text{Smi}^M = (w_G{}^M - w_{WILT}{}^M) / (w_{FC}{}^M - w_{WILT}{}^M) \qquad (5a)$$

$$\text{Smi}^O = (w_G{}^O - w_{WILT}{}^O) / (w_{FC}{}^O - w_{WILT}{}^O) \qquad (5b)$$

where the superscripts *M* and *O* denote "model" and "observation" data.

3.2 Model calibration

The file of the input parameters of ISBA is given in Table 2. Most of the soil input parameters given in Table 2 are site-dependent. There are obtained from measurements, or they are prescribed to the usual value used over the Avignon experimental site. "Model" and "observation" field capacity parameters ($w_{FC}{}^M$ and $w_{FC}{}^O$) are set equal to 0.31 m^3/m^3, which is the usual value obtained from field observations. The value of the "observation" wilting point $w_{WILT}{}^O$ is set equal to the value obtained from measurements and corresponding to a soil water potential ψ_S = -1.5 MPa ($w_{WILT}{}^O = 0.13\ m^3/m^3$). Due to the strong vertical gradients of the soil characteristics, as illustrated in Table 1, it is difficult to prescribe *a priori* a value for the "model" wilting point $w_{WILT}{}^M$. This parameter is very important since it is used in the parameterizations of the soil water transfers. Also, it is used to compute the soil moisture index given by Eq.(5a), from the simulated soil moisture data. Therefore, the value of $w_{WILT}{}^M$ is calibrated by minimizing the root mean square error (rmse) C_S between the measured and simulated values of Smi in 1990:

$$C_S = 1/N\ \Sigma\ (\text{Smi}^O - \text{Smi}^M)^2 \qquad (6)$$

where N is the number of data used to compute the soil moisture indexes Smi^O and Smi^M, defined in Eq.(5a) and Eq.(5b). The retrieved value for $w_{WILT}{}^M$ (0.18 m^3/m^3) is within the range of variations given in Table 1, in the [20-80cm] soil layer.

Most of the parameters describing the soybean canopy were already calibrated to simulate the surface fluxes over soybean crops during the Hapex-Mobhily large scale experiment, in South-western France (Mahfouf and Noilhan, 1996). The only vegetation parameter which is calibrated from the Avignon data set, is the minimum stomatal conductance r_{Smin}, to account for possible agronomical differences between the soybean crops. As in Calvet et al. (1998), the calibration of r_{Smin} is obtained by minimizing the cost function representing the error in the description of the energy and mass fluxes at the surface - atmosphere interface. We obtained different values for r_{Smin} (r_{Smin}=80 s/m in 1989 and r_{Smin}=200 s/m in 1990) which may be partly related to crop variety and to irrigation. In particular, irrigation was more intensive in 1989 and may have significantly stimulated the development of the root system and thus water uptake capabilities.

3.3 Inversion process

After this step of model calibration, the soil reservoir R_2 (mm) as defined in Eq.(3) is retrieved from the time variations of the surface soil moisture index in 1989. R_2 is obtained by minimizing the rms error C_S, as defined in Eq.(6), between the daily measured and simulated surface soil moisture indexes. The value of $R_2(t)$ at date t is retrieved from the minimization of the cost function C_S computed from a time series of Smi comprised between the dates t and t + T_J, where T_J is the integration period of time. In order to study the sensitivity of the retrieval process to the time repetition of the surface observations, C_S is computed using values of Smi every N_R days (N_R (day^{-1}) is the time repetitivity of the surface measurements, N_R=1 (daily measurements), 2, 3). In the following, the retrieval acuracy of R_2 is computed as a function of the two parameters T_J and N_R.

4 Results and Discussion

In order to check the field hydrological characteristics are correctly reproduced, the ISBA simulations are tested against the measured data. Simulations of the soil moisture index and the soil reservoir R_2 (mm) are compared with the measured data in 1990 and in 1989. The rms error and mean bias between measured and simulated values of Smi and R_2 are given in Table 3, in 1989 and 1990. The "model" wilting point w_{WILT}^{M} was calibrated to minimize the rms error between observed and simulated soil moisture indexes in 1990. Using this calibrated parameter, a very good agreement between observations and simulations is also obtained in 1989 for Smi. Using a measured data to initialize the soil reservoir R_2, (R_2 = 403 mm on DoY 209 in 1990; R_2 = 391.3 mm on DoY 200 in 1989), the time variations of R_2 are very correctly simulated in 1990 and in 1989 (Table 3).

After this step of direct simulation, the model inversion is carried out in 1989. The retrieval of the soil reservoir R_2 at date t is performed from measured time series of the surface soil moisture index comprised between the dates t and t+T_J. The inversion process is carried out every day, with date t varying from DoY 200 to DoY 268 (for T_J = 10 days) or to DoY 258 (for T_J = 20 days). During the period [t, t+T_J], the surface data are included in the retrieval process with a N_R-day temporal repetitivity

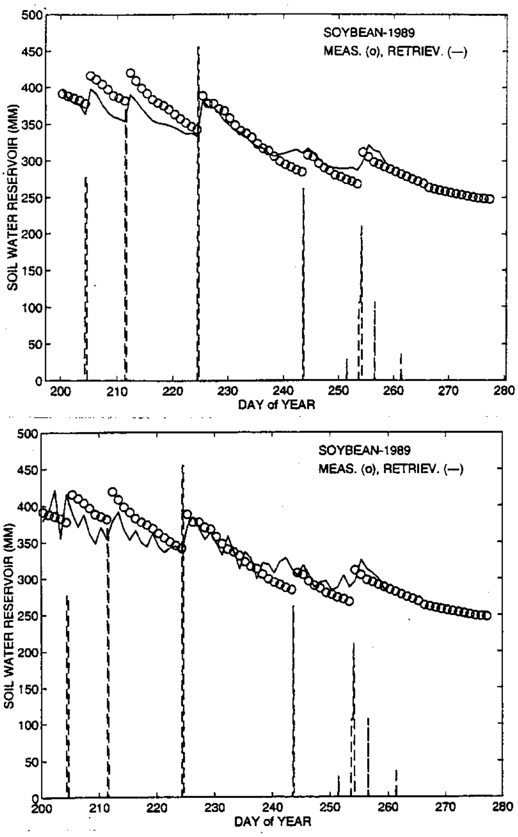

Fig. 1a-b Comparison between measurements and retrievals of the time variations of the soil water content in the root-zone R_2 (mm) for two configurations of the retrieval process (T_J=20 days, N_R=1 day^{-1}) (a) and (T_J=20 days, N_R=3 day^{-1}) (b). The vertical bars represent the hourly rate of precipitation and irrigation (amount of water (mm) per hour X 50).

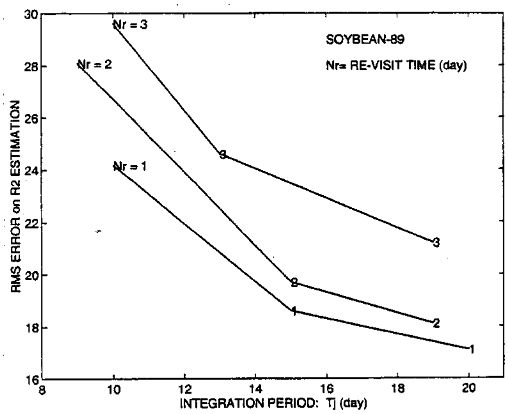

Fig. 2 Rms error between measurements and retrievals of the soil water content in the root-zone R_2 (mm), computed over the whole crop cycle, as a function of the integration period T_j (day) and for three values of the measurement repetitivity N_R (day^{-1}).

Table 1. Measured values of the wilting point w_{WILT} and field capacity w_{FC} at [0-20cm] and at [20-80cm]. w_{WILT} and w_{FC} are computed for a soil water potential ψ_s = -1.5 MPa, and ψ_s = -0.033 MPa, respectively. The measured data are given in kg/kg (from Chanzy, 1991). The range of variations of the volumetric data (m³/m³) are calculated using dry bulk density $\rho_b \approx$ 1.2-1.5 g/cm³ at the soil surface ([0-20cm]) and $\rho_b \approx$ 1.4-1.7 g/cm³ at depth ([20-80cm]).

	Wilting point w_{WILT} (kg/kg)	Wilting point w_{WILT} (m³/m³) Range of variations	Field capacity w_{FC} (kg/kg)	Field capacity w_{FC} (m³/m³) Range of variations
Surface ([0-20cm])	0.1	0.12-0.15	0.187	0.224-0.280
At depth [20-80cm]	0.124	0.173-0.210	0.183	0.256-0.311

Table 2. ISBA soil and vegetation parameters for Soybean (1989 and 1990)

Definition	Symbol and Value	Source
SOIL:		
Texture:		measured
sand fraction (%)	Sand=11	
clay fraction (%)	Clay=27	
Soil depth (m)	d_2=1.3	prescribed
Wilting point (m³/m³):	$w_{WILT}{}^M$=0.18	calibrated in 1990
Field Capacity (m³/m³):	$w_{FC}{}^M$=0.31	prescribed
Water transfer coefficient	C_1/d_1=300	(MN91)*
VEGETATION		
vegetation coverage	veg=0.45.LAI, if LAI≤1	(MN96)**
	veg=0.15.LAI +0.3, if LAI>1	
albedo	A=0.22	(MN96)
Thermal emissivity	ε_s=1	(MN96)
Minimum stomatal conductance (sm⁻¹)	R_s=200 , for SOYBEAN-90	calibrated
Roughness length (m)	R_s=80 , for SOYBEAN-89	
Roughness length ratio	z_0=0.13 Hc (Hc=crop height)	(MN96)
Displacement Height (m)	z_0/z_{0h}=10	(MN96)
	d=0.7.Hc (Hc=crop height)	(MN96)

*MN91 is for (Mahfouf and Noilhan, 1991); **MN96 is for (Mahfouf and Noilhan, 1996)

Table 3. Results of direct simulations: rms error and mean bias between measured and simulated surface Smi and soil water reservoir R_2 (mm) in 1989 and 1990.

	Soil moisture Index Smi at the soil surface ([0-5cm])		Total soil water content [0- 1.3m] (R_2, mm)	
	RMS error	Bias	RMS error	Bias
Soybean 89	0.295	0.12	6.9	4.2
Soybean 90	0.254	0.086	5.2	1.6

(N_R=1 day^{-1} corresponds to the use of daily surface data; N_R=2 day^{-1} corresponds to one day out of two, ...). The results of the retrieval process are given in Table 4. Table 4 lists the rms error and the mean bias between measured and retrieved soil water reservoir R_2 (mm) as a function of the parameters T_j (day), the time period and N_R (day^{-1}), the measurement repetitivity. The results are illustrated in Fig.1a-b, for the case T_j=20 days and N_R = 1 day^{-1} (a) or N_R = 3 day^{-1} (b).

Table 4. Results of retrievals: rms error and mean bias between measured and retrieved soil water reservoir R_2 (mm) in 1989 as a function of two parameters of the retrieval process: T_j, the time period (day) and N_R, the measurement repetitivity (day^{-1}) (N_{mes} is the measurement number).

Time Period* T_j (day)	Measurement repetitivity N_R (day^{-1})	Measurement Number N_{mes}	RMS Error (mm)	Mean Bias (mm)
10	1	10	24.16	3.0
9	2	5	28.1	5.9
10	3	4	29.6	5.9
15	1	15	18.6	-2.2
15	2	8	19.7	-1.6
13	3	5	24.6	1.02
20	1	20	17.1	-5.3
19	2	10	18.1	-4.0
19	3	7	21.2	-2.6

*$T_i = N_R \cdot (N_{mes} - 1) + 1$

It can be seen in Fig.1a that the retrieval process produces very correct estimates of the time variations of the soil reservoir R_2 during the 60-day retrieval period of time. If the time repetitivity of the surface data included in the retrieval process decreases up to N_R = 3 day^{-1}, the retrieved values of R_2 are still very correct in terms of rms error and bias, but the time variations are slightly irregular (Fig.1b).

The results given in Table 4, are illustrated in Fig.2. In the latter figure, the rms error on the retrieved estimate of R_2 (mm), is displayed as a function of the integration period T_j, for three values of the temporal repetitivity N_R (N_R=1, 2 or 3 day^{-1}). The rms error decreases steadily when the integration period increases. It appears that the value of the rms error should not change much if T_j is increased beyond 20-30 days. It seems that beyond this range of variations for T_j, the retrieval accuracy remains limited by the model accuracy in the simulations of the hydrological characteristics. The rms error is also strongly sensitive to the value of N_R. In terms of retrieval error, a high temporal repetitivity N_R can partly compensates for a short period of integration. However, for a given number of surface measurements N_{mes}, it seems it is preferable to use a long integration period than a high temporal repetitivity. For instance, for the given value N_{mes}=10, rmse=24.16 mm is obtained for the retrieval configuration (T_j = 10 days, N_R=1 day^{-1}), while the rmse is significantly lower (18.1 mm) for T_j = 20 days and N_R=2 day^{-1}.

5 Conclusion

The general approach developed in this work is to use the 1990 data set to calibrate the ISBA parameterization of the soil water transfers, while the retrieval process is based on the 1989 data set, in which the soil moisture characterization was more exhaustive. Once calibrated, ISBA simulates very correctly the soil moisture at depth and in the top surface layer, both in 1990 and in 1989. The results of the retrieval process show the large potential interest in the temporal information of surface soil moisture variations to derive hydrologic variables at depth. The retrieved soil moisture content in the root-zone is a key variable to parameterize the soil water transfers and water availability for the vegetation transpiration processes.

This work contributes to better define the requirements for the use of remotely-sensed microwave observations of surface soil moisture. The sensitivity of the retrieval process to the integration period T_j and to the temporal repetitivity N_R of the surface observations included in the computations, is analysed. These aspects are key research issues, if we consider (1) the increasing potential of microwave RS technology and the future spaceborne programs which are currently evaluated by Space Agencies (2) and the fundamental needs for characterization of soil water transfers to calibrate and initialize land surface transfer schemes in atmospheric and hydrological models.

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