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Estimating root zone soil moisture from surface soil moisture data and soil-vegetation-atmosphere transfer modeling

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Abstract. We studied the possibility of estimating root zone soil moisture through the combined use of a time series of observed surface soil moisture data and soil-vegetation-atmosphere transfer modeling. The analysis was based on the interactions between soil-biosphere-atmosphere surface scheme and two data sets obtained from soybean crops in 1989 and 1990. These data sets included detailed measurements of soil and vegetation characteristics and mass and energy transfer in the soil-plant-atmosphere system. The data measured during the 3-month experiment in 1989 are used to investigate the accuracy of soil reservoir retrievals, as a function of the time period and frequency of measurements of surface soil moisture involved in the retrieval process. This study contributes to better defining the requirements for the use of remotely sensed microwave measurements of surface soil moisture.

1. Introduction

Passive microwave remote sensing systems can now provide information on surface soil moisture [*Schmugge and Jackson*, 1994; *Jackson et al*., 1995; *Wigneron et al*., 1995, 1996]. Using aperture synthesis technology, passive microwave sensors can estimate soil moisture on a regular (daily) basis and at a regional scale (~10 km) [*Le Vine et al*., 1994; *Kerr et al*., 1997; *Wigneron et al*., 1998]. Such systems would be very useful for characterizing soil moisture, which is highly variable, in terms of space and time.

Microwave remote sensing (RS) systems can provide information on the moisture content of the upper layers of the soil surface (~0–5-cm top soil layer). In hydrology and meteorology the near-surface soil water content is a key variable for accurately estimating water exchange between the surface and the atmosphere [*Chanzy and Bruckler*, 1993; *Daamen and Simmonds*, 1996]. Microwave RS techniques cannot, however, provide direct estimates of water availability to plants since this requires estimating soil moisture in the root zone. Water availability to plants is an important variable for evaluating vegetation transpiration, as well as a key factor in the energy and water budgets of crop canopies and a basic factor in mesoscale atmospheric circulation models [*Noilhan and Calvet*, 1995].

In order to estimate the soil water content in the root zone from a time series of observed surface soil moisture it is necessary to use a tool which "assimilates" the temporal information on the land surface provided by the RS data. Soil-vegetation-atmosphere transfer (SVAT) models, which simulate the energy and mass fluxes at the soil-vegetation-atmosphere interface, are suitable tools for performing this integration [*Olioso et al*., 1999]. Several recent studies have investigated the possibility of assessing the water content in the upper 1- or 2-m soil layer through 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 values was performed by *Calvet et al*. [1998] using a continuous series of micrometeorological data measured on a fallow site in 1995 (Monitoring the Usable Soil Reservoir Experimentally (MUREX) experiment). The study was based on the Interactions between Soil-Biosphere-Atmosphere (ISBA) surface scheme [*Noilhan and Planton*, 1989], which is used in the operational simulations of the French weather forecast model Action de Recherche Petite Echelle-Grande Echelle (ARPEGE). 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 near-surface soil moisture every 2–4 days during the 15-day period was sufficient to obtain good estimates of w_2. Promising results were obtained during two 30-day observation periods in spring and autumn 1995. This study was based on data obtained over a short period of time, and the sensitivity of the data retrieval process as a function of the time frequency and integration period of the surface data could not be investigated. The model calibration and the assimilation of data were based on the same data set. It is important to evaluate the efficiency of the proposed method and to show that for a given set of soil-vegetation conditions the

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model calibration remains constant, regardless of atmospheric forcing. These are key questions which must be addressed to demonstrate the potential interest of such a method for applications in the fields of hydrology, meteorology, and agriculture and to prepare future space missions.

The present study investigated these aspects using two data sets collected during the vegetation cycle of a soybean crop in 1989 and 1990 in Avignon. They included detailed measurements of the soil and vegetation characteristics and the energy and mass transfer in the soil-vegetation-atmosphere continuum. The two soybean data sets included strongly contrasting surface characteristics (in terms of soil moisture, surface temperature, and vegetation biomass) over a 2- and 3-month period of time due to irrigation, rainfall events, and the short duration of the crop cycle (~3.5 months). The 1990 data set was used to calibrate the ISBA simulations for a soybean crop. The ISBA simulations of fluxes and soil moisture values, both at the surface and at depth, were tested against the data collected in 1989 and 1990. The requirements for using surface soil moisture data in the retrieval process of the stored root zone soil moisture was investigated using the 1989 data set, which included observations made over a 3-month period. This study contributes to analyzing the potential interest of frequent surface soil moisture estimations, which could be made from spaceborne RS measurements at a 1–5-day interval. The analysis of a time series of observed surface soil moisture, over a 10–30-day period, is very relevant since it could largely contribute to support the development of spaceborne microwave remote sensing systems.

2. Soybean Data Sets

The two data sets used in this study were collected during the vegetation cycle of a soybean crop by two different teams of the Institut National de la Recherche Agronomique (INRA) 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 at the same site, a silty clay loam experimental field, from the beginning of July to the end of October 1989 and from the beginning of July to the end of September 1990. The data set period comprises day of year (DOY) 200–278 in 1989 and 209–258 in 1990.

2.1. Flux and Vegetation Observations

The soybean crop cultivar used in 1989 (*Glycine max* cultivar Weber) was different from that in 1990 (cultivar Labrador), but both cultivars have very similar structural and phenological characteristics. In 1989 the crop received 233 mm of water from both rainfall and irrigation, and the initial soil water content was close to field capacity. The crop reached a maximum leaf area index (LAI) of 4.9 on DOY 236. In 1990 the crop received less irrigation water (total amount of water was 123 mm), and the initial soil water content was equal to field capacity. The crop reached a maximum LAI of 3.8, a value significantly smaller than in 1989. The data sets included continuous measurements of soil and vegetation characteristics and of energy and mass transfer, obtained from classical meteorological observations combined with surface and water budget measurements. In 1989 the emphasis was on the soil water balance, and a detailed characterization of the soil water transfer was performed [*Bertuzzi et al.*, 1992]. Conversely, in 1990 the emphasis was placed on vegetation flux characterization, and vegetation water potential, stomatal conductance, and leaf photosynthesis were measured for several days [*Olioso et al.*, 1996].

During both experiments, incident radiation, air temperature, wind speed, and vapor pressure were recorded above the canopy. The energy balance was monitored using various sets of instruments and the evapotranspiration flux L_E was derived from measurements of net radiation R_n, ground heat flux G_S and sensible heat flux H (all terms are expressed in W m^{-2}) with Bowen ratio and eddy correlation methods. It should be noted that for 1989, because of technical problems with the eddy correlation device, ~50% of the hourly evapotranspiration data are missing in the data set (missing data can be found during 47 days over the DOY 200–278 period).

The vegetation characteristics were monitored throughout the crop cycle (in terms of wet and dry biomass (kg m^{-2}), LAI, crop height H_C (in m), leaf angle distribution, and canopy structure). Thermal infrared brightness temperatures were continuously measured using radiometers (8–14 μm) in vertical orientation.

2.2. Soil Characteristics

Soil water content profiles, from 20 cm to ~1.6 m depth at 10 cm intervals, were recorded daily in 1989 and on a 2- or 3-day basis in 1990 with neutron probes. These moisture profiles were performed to obtain the water storage variations of the root zone reservoir, with a high temporal resolution. In the upper 20-cm soil layer, accurate moisture profiles were obtained daily in 1989 at ~0800 UT from gravimetric measurements at 0–1, 1–2, . . . , 4–5, 5–7, 7–10, 10–15, and 15–20 cm. In 1990, only the top 0–5- or 5–10- and 10–20-cm soil layers were sampled at the same time, on a 1- or 2-day basis. Soil moisture characterization was therefore more exhaustive in 1989. Dry bulk density was measured using a field transmission gamma ray probe [*Bertuzzi et al.*, 1987] at depths of 2–160 cm. The volumetric water content was computed from measurements of the gravimetric water content and of dry bulk density. Soil temperature was automatically measured with platinum resistance temperature probes inserted at different depths (1, 2, 5, 10, 20, and 50 cm).

An estimate of soil moisture at field capacity w_{FC} and at wilting point W_{WILT} was obtained from the relationship between soil water potential and gravimetric water content computed by *Chanzy* [1991] for two layers, 0–20 and 20–80 cm. Wilting point and field capacity were computed for a soil with water potential $\psi_S = -1.5$ and -0.033 MPa, respectively. Over the range of variations in dry bulk density ρ_b (g cm^{-3}), from the surface to 80-cm depth, the possible range of variations in w_{FC} (m^3 m^{-3}) and w_{WILT} (m^3 m^{-3}) are given in Table 1. To calibrate ISBA, it is usually assumed that the water content at field capacity w_{FC} corresponds to a value of hydraulic conductivity of 0.1 mm d^{-1} [*Noilhan and Mahfouf*, 1996]. In addition, the wilting point w_{WILT} depends not only on soil characteristics but also on vegetation type. Therefore the range of variations in w_{FC} and w_{WILT} given in Table 1 are only indicative, but they are useful for model calibration. From field observations after rainfall events at the Avignon test site, soil moisture at field capacity usually ranged between 0.31 and 0.33 m^3 m^{-3}. This corresponds to the higher values of w_{FC} in Table 1.

Table 1. Measured Values of the Wilting Point w_{WILT} and Field Capacity w_{FC} at Surface and at Depth

	Wilting Point w_{WILT}, kg kg^{-1}	Wilting Point Range of Variations, m^3 m^{-3}	Field Capacity w_{FC}, kg kg^{-1}	Field Capacity Range of Variations, m^3 m^{-3}
Surface (0–20 cm)	0.100	0.120–0.150	0.187	0.224–0.280
Depth (20–80 cm)	0.124	0.173–0.210	0.183	0.256–0.311

Values of w_{WILT} and w_{FC} were computed by *Chanzy* [1991]. The range of variations is given in m^3 m^{-3} using dry bulk density $\rho_b \approx 1.2$–1.5 g cm^{-3} at 0–20 cm and $\rho_b \approx 1.4$–1.7 g cm^{-3} at depth (20–80 cm).

3. Method

The first step of the study is model calibration, which consists of specifying the input parameters of ISBA. The second step is the inversion process, which consists of retrieving the root zone soil moisture w_2 from the time variations of the near-surface soil moisture characteristics. The value of $w_2(t)$ at date t was obtained by minimizing the rms error between the daily measured and simulated near-surface soil hydrological characteristics. The rms error was computed from a time series of measured near-surface data between dates t and $t + T_J$, where T_J is the integration time period.

The general approach adopted in this paper was to calibrate the ISBA parameters for soil water transfer using the 1990 data set. In 1989, soil moisture data were available for a longer period of time than in 1990, and the retrieval process was performed using the 1989 data set.

3.1. ISBA Surface Scheme

The ISBA land surface scheme was developed by Météo-France and described by *Noilhan and Planton* [1989]. The relevance of the scheme has been shown with regard to vegetated and bare surfaces [*Mahfouf and Noilhan*, 1991; *Noilhan and Mahfouf*, 1996; *Calvet et al.*, 1998]. 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 of bare soils and vegetated surfaces. The ISBA scheme, used in this study, is a simple model with few input parameters which can easily be coupled with remotely sensed data of surface variables for assimilation and retrieval processes. The ISBA model predicts the time variations of five main variables: surface temperature T_S, volumetric water content w_G (m^3 m^{-3}) at the soil surface, mean soil temperature T_2, the mean volumetric water content w_2 (m^3 m^{-3}) in the root zone, and the water content of an interception reservoir W_r. In this study, surface soil moisture w_G is the volumetric moisture content of the surface soil layer (0–5 cm). This layer thickness is commonly used with ISBA. Moreover, it corresponds well with the sampling depth of low-frequency microwave RS measurements.

The ISBA model was driven by measurements of the following atmospheric forcing variables on a 30-min basis: incoming radiation, rainfall, atmospheric pressure, air temperature, air humidity, and wind speed at a reference level. Two vegetation characteristics, LAI and crop height H_C, obtained from ground measurements, were ascribed on a daily basis. The five main variables, T_S, T_2, w_G, w_2 and W_r, were initialized at the beginning of the simulation period. Since a detailed description of the ISBA scheme can be found in several studies [*Noilhan and Planton*, 1989; *Noilhan and Mahfouf*, 1996], only a brief description of the water transfer 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

$$\delta w_G/\delta t = C_1/(\rho_w d_1)(P_G - E_G) - C_2/\tau_1\,(w_G - w_2)$$

$$0 \le w_G \le w_{\mathrm{SAT}} \tag{1}$$

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

The first term on the right of (1) represents the influence of surface atmospheric fluxes (outputs due to soil evaporation E_G and inputs due to rainfall and irrigation P_G. The second term in (1) characterizes the diffusivity of water in the soil which tends to restore surface soil moisture w_G to the bulk value w_2, and τ_1 is a restore constant of 1 day. The dimensionless coefficients C_1 and C_2 are highly dependent on 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 in (2) is similar to that in (1), and it is computed as a function of P_G, E_G, transpiration rate E_{TR}, and gravitational drainage, parametrized by the dimensionless coefficient C_3. The value we used for C_1 was obtained by *Mahfouf and Noilhan* [1991] (hereafter referred to as MN91) from model calibration at the same test site ($C_1/d_1 = 300$). As in MN91 the values of the two other soil parameters C_2 and C_3 in (1) and (2) were obtained from the ISBA subroutines as a function of the soil type (the soil of the Avignon test site is a silty clay loam). 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):

$$R_2 = 1000\,(w_2\,d_2). \tag{3}$$

Equation (1) relates the time variations of surface soil moisture w_G to the variables of interest (E_G and w_2). Consequently, if good estimates of P_G can be obtained from the ground meteorological network, periodic observations of w_G will provide information on soil evaporation E_G and on root zone water content w_2. In this study, the retrieval process of w_2 from temporal information on w_G is based on this assumption.

Water vapor flux E is the sum of soil evaporation E_G and of vegetation evaporation E_V, which are given by

$$E_G = [(1 - \mathrm{veg})\rho_a/R_a][h_u q_{\mathrm{sat}}(T_S) - q_a] \tag{4}$$

$$E_V = (\mathrm{veg}\;\rho_a h_v/R_a)[q_{\mathrm{sat}}(T_S) - q_a], \tag{5}$$

where veg is the fraction of vegetation cover, ρ_a and q_a are the air density and specific humidity at atmospheric level z_a, $q_{\mathrm{sat}}(T_S)$ is the saturated specific humidity at temperature T_S,

R_a is the aerodynamic resistance, and h_u is the relative humidity at the ground surface. Coefficient h_v can be written as a function of aerodynamic resistance R_a, surface resistance R_S, and the fraction of foliage covered by intercepted water δ:

$$h_v = (1 - \delta) R_a/(R_a + R_S) + \delta. \tag{6}$$

Surface resistance R_S is given by

$$R_S = (R_{s\min}/\mathrm{LAI}) F_1 F_2^{-1} F_3^{-1} F_4^{-1}, \tag{7}$$

where functions F_1, F_2, F_3, and F_4 parametrize the effects of photosynthetically active radiation, water availability in the root zone, vapor pressure deficit of the air, and temperature dependence of stomatal resistance. The expressions for these functions can be found in several papers [*Noilhan and Planton*, 1989, 1996]; therefore they are not detailed in this section. However, it is important to describe function F_2 since it parametrizes water availability for transpiration in the root zone. Function F_2 is directly related to the mean soil moisture w_2 as follows:

$$\begin{aligned} &F_2 = (w_2 - w_{\mathrm{WILT}})/(w_{FC} - w_{\mathrm{WILT}}) \qquad w_{\mathrm{WILT}} \le w_2 \le w_{\mathrm{FC}} \\ &F_2 = 1 \qquad w_2 > w_{FC} \\ &F_2 = 0 \qquad w_2 < w_{\mathrm{WILT}}. \end{aligned} \tag{8}$$

In (4), relative humidity h_u is related to surface soil moisture w_G as follows:

$$\begin{aligned} h_u &= 0.5[1 - \cos(\pi w_G/w_{FC})] \qquad w_G < w_{FC} \\ h_u &= 1 \qquad w_G \ge w_{FC}. \end{aligned} \tag{9}$$

Equations (4)–(9) are given in this section to illustrate the link between soil evaporation E_G and vegetation evaporation E_V fluxes and soil moisture content at depth w_2 and at the soil surface w_G. In particular, it can be seen that the two soil parameters w_{WILT} and w_{FC} are used to normalize soil moisture contents w_G and w_2 in the parameterizations of the water fluxes set out in (8) and (9).

Previous results with ISBA showed that simulations of near-surface soil moisture w_G overestimated the data measured in 1990. This discrepancy could be partly related to the fact that ISBA does not account for the vertical gradients of soil characteristics, in terms of soil texture, structure, and density. For instance, a single effective value for wilting point is used for the whole soil layer from the surface to soil depth d_2, whereas ground measurements indicate that there is a rather strong vertical gradient for this soil parameter (see Table 1). Therefore, to compare measured and simulated near-surface soil hydrological characteristics using ISBA, it was necessary to normalize observations and simulations of surface soil moisture [*Douville*, 1998]. The "model" and "observation" normalized soil moisture values (W^M and W^O, respectively) are given by

$$W^M = (w_G^M - w_{\mathrm{WILT}}^M)/(w_{FC}^M - w_{\mathrm{WILT}}^M) \tag{10a}$$

$$W^O = (w_G^O - w_{\mathrm{WILT}}^O)/(w_{FC}^O - w_{\mathrm{WILT}}^O), \tag{10b}$$

where the superscripts M and O denote model and observation data. In (10a) the model parameters w_{FC}^M and w_{WILT}^M (ISBA effective parameters in the 0–1.3-m soil layer) are used to normalize the modeled surface soil moisture (w_G^M); in (10b) the observation parameters w_{FC}^O and w_{WILT}^O (measured in the 0–5-cm soil layer) are used to normalize the observed near-surface soil moisture (w_G^O).

By combining (10a) and (10b) the agreement between modeled and observed normalized soil moisture at the soil surface ($W^M = W^O$) can be written as

$$w_G^O = A_N(w_G^M - w_{\mathrm{WILT}}^M) + w_{\mathrm{WILT}}^O \tag{11a}$$

$$A_N = (w_{FC}^O - w_{\mathrm{WILT}}^O)/(w_{FC}^M - w_{\mathrm{WILT}}^M). \tag{11b}$$

In the following the simulations of near-surface soil moisture w_G^M are calibrated using the linear equation (11a). The computing of the four soil parameters w_{FC}^M, w_{WILT}^M, w_{FC}^O, and w_{WILT}^O used in (11a) is described in section 3.2.

3.2. Model Calibration

3.2.1. Soil parameters. The calibration of the ISBA input parameters was based on the 1990 data set. The parameters, which were kept constant during the whole vegetation cycle, are provided in Table 2. Most of the soil input parameters presented in Table 2 are site-dependent. They were obtained from measurements or set at a common value representing the Avignon experimental site.

Table 1 shows a rather low vertical gradient for field capacity. Thus parameters w_{FC}^M and w_{FC}^O were set equal at a value commonly obtained from field observations (0.31 $\mathrm{m^3\ m^{-3}}$). Conversely, it was difficult to ascribe a value to w_{WILT}^M and w_{WILT}^O since the value of the wilting point is crop-dependent, and there is a significant vertical gradient for this parameter (Table 1 shows a range of w_{WILT} values of 0.12–0.21 $\mathrm{m^3\ m^{-3}}$ over the 0–80-cm soil layer). The values of w_{WILT}^M and w_{WILT}^O were obtained for a soil water potential $\psi_S = -1.5$ MPa from Table 1: w_{WILT}^O was set equal to near-surface soil water content ($w_{\mathrm{WILT}}^O = 0.13\ \mathrm{m^3\ m^{-3}}$), while w_{WILT}^M was set equal to soil water content at depth (0.18 $\mathrm{m^3\ m^{-3}}$).

To verify that the values of field capacity and wilting point selected for the surface and the model were realistic ($w_{FC}^O = 0.31$, $w_{FC}^M = 0.31$, $w_{\mathrm{WILT}}^O = 0.13$, and $w_{\mathrm{WILT}}^M = 0.18$), simulations and observations of near-surface soil moisture w_G were compared for 1990. The comparison is presented in Figure 1. The rms error C_S and the bias B_S between the measured and simulated values of w_G were computed using all the surface data available, on a 1- or 2-day basis, during the period DOY 209–258 in 1990. Both values of C_S and B_S obtained in 1990 ($C_S = 0.033\ \mathrm{m^3\ m^{-3}}$ and $B_S = 0.011\ \mathrm{m^3\ m^{-3}}$) were low in comparison to the range of variations in w_G and showed that the simulations of w_G were in good agreement with the observations.

3.2.2. Vegetation parameters. Most of the parameters describing the soybean canopy have been calibrated by *Mahfouf and Noilhan* [1996] to simulate the surface fluxes over soybean crops during the Hydrologic Atmospheric Pilot Experiment (HAPEX)-Mobilhy large-scale experiment in southwestern France. The only vegetation parameter which was calibrated from the Avignon data set was the minimum stomatal conductance $r_{S\min}$, to account for possible agronomic differences between the soybean cultivars. The ability of the crop to use soil water at depth depends on the canopy type and cultivar, the cultural practices, the sowing date, etc., which significantly influence the development of the root system. The calibration of $r_{S\min}$ was performed using the 1990 data set. As by *Calvet et al.* [1998], the calibration of $r_{S\min}$ was obtained by minimizing the cost function C_F, which represents the error in the description of the energy and mass fluxes at the surface-

Table 2. Interactions Between Soil-Biosphere-Atmosphere (ISBA) Soil and Vegetation Parameters for Soybean (1989 and 1990)

Definition	Symbol and Value	Source
	Soil	
Texture		measured
Sand fraction, %	11	
Clay fraction, %	27	
Soil depth, m	$d_2 = 1.3$	measured
Wilting point, $m^3\ m^{-3}$	$w^M_{\mathrm{WILT}} = 0.18$	ascribed
Field capacity, $m^3\ m^{-3}$	$w^M_{FC} = 0.31$	ascribed
Water transfer coefficient	$C_1/d_1 = 300$	MN91*
	Vegetation	
Vegetation coverage	veg = 0.45 LAI, if LAI ≤ 1 veg = 0.15 LAI + 0.3, if LAI > 1	MN96†
Albedo	$A = 0.22$	MN96
Thermal emissivity	$\varepsilon_s = 1$	MN96
Minimum stomatal resistance	$r_{S\min} = 206.0$ s m^{-1}	calibrated from 1990 data
Roughness length, m	$z_0 = 0.13\ H_c$	MN96
Roughness length ratio	$z_0/z_{0h} = 10$	MN96
Displacement height, m	$d = 0.7\ H_c$	MN96

**Mahfouf and Noilhan* [1991]
†*Mahfouf and Noilhan* [1996]

atmosphere interface (this term will be referred to as global flux error):

$$C_F = \{(1/N)[\Sigma(R_n^O - R_n^M)^2 + \Sigma(H^O - H^M)^2 + \Sigma(L_E^O - L_E^M)^2]\}^{1/2} \quad (12)$$

where N is the number of values used to compute the hourly fluxes R_n, H, and L_E during the entire crop cycle. C_F was minimized in this study based on the Simplex algorithm (e04ccf.f Fortran subroutine of the Numerical Algorithms Group (NAG) library [*NAG*, 1990]).

The value of $r_{S\min}$ (206.0 s m^{-1}) obtained at the Avignon test site was slightly higher than the value ($r_{S\min} = 150$ s m^{-1}) obtained by *Mahfouf and Noilhan* [1996] in HAPEX-Mobilhy. This difference may reveal a different behavior in water flux control of the crop between the two test sites. Using the calibrated value of $r_{S\min}$, the global flux error C_F was 37.0 W m^{-2}. The rms error and the mean bias between the simulated and measured values of the main components of the water and energy balance (net radiation R_n, sensible heat flux H, evapotranspiration L_E, and ground heat flux G_S are provided in Table 3. The bias, computed over a 2-month period (DOY 209–258), was small for all components R_n, H, L_E, and G_S. The rms error was relatively similar for the different components and varied from ~30 to 40 W m^{-2}. These results were rather encouraging, if we consider the fact that the constant values of the soil and vegetation parameters in Table 2 were used to calibrate ISBA over a 2-month period including vegetation development and senescence.

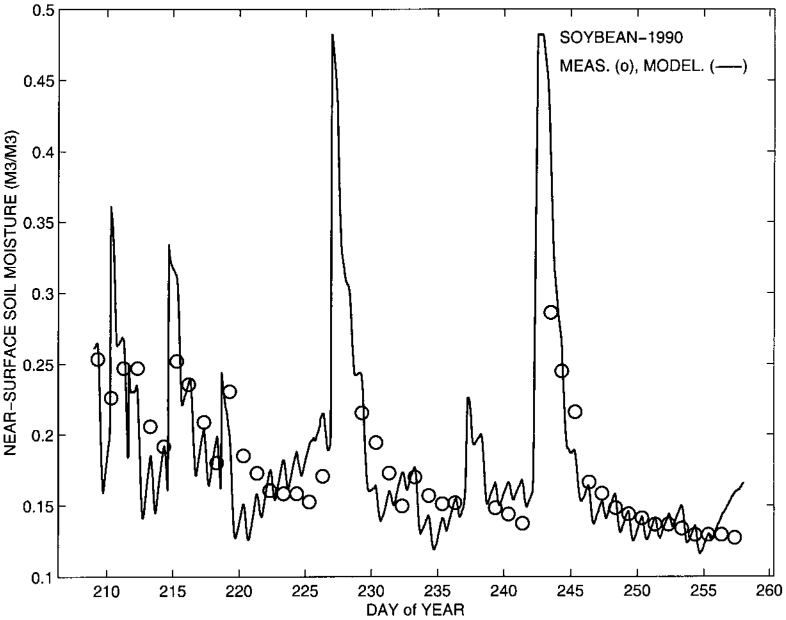

Figure 1. Comparison between measurements and simulations of near-surface soil moisture w_G in 1990.

Table 3. Comparison Between Measured and Simulated Flux Densities in Terms of Root-Mean-Square Error and Bias

	Fluxes, W m^{-2}			
	Net Radiation R_n	Sensible Heat Flux H	Evapotranspiration L_E	Ground Heat Flux G_s
		Soybean 1990		
Root-mean-square error	40.6	29.6	39.9	39.8
Bias	−1.5	5.0	−10.85	4.4
		Soybean 1989		
Root-mean-square error	35.5	32.65	42.6	29.3
Bias	7.4	15.2	−17.1	6.4

3.3. Inversion Method

To summarize section 3.2, most of the model parameters were obtained from measurements or from previous calibration during the HAPEX-Mobilhy experiment. The values ascribed to soil parameters w_{FC}^{O}, w_{FC}^{M}, w_{WILT}^{M} were partially validated by comparing simulations and measurements of surface soil moisture using the 1990 data set. The minimum canopy surface resistance $r_{S\min}$ was calibrated using the 1990 flux data.

After this step of model calibration based on the literature [*Mahfouf and Noilhan*, 1991, 1996] and the 1990 data set, values for soil reservoir R_2 (mm), as defined in (3), were retrieved from the time variations of surface soil moisture using the 1989 data set. R_2 was obtained by minimizing the rms error C_S between the daily measured and simulated surface soil moisture. The value of R_2 (t) at date t was retrieved by minimizing the cost function C_S, computed from a time series of observed w_G data comprised between dates t and $t + T_J$, where T_J is the integration period of time.

The C_S error was minimized in the same way as for model calibration in section 3.2. To study the sensitivity of the data retrieval process to the time frequency of the surface observations, C_S was computed using values of w_G every N_R days (N_R (day^{-1}) is the time frequency of the surface measurements: $N_R = 1$ day^{-1} corresponds to the use of daily surface data, $N_R = 2$ day^{-1} corresponds to 1 out of 2 days, etc.). To illustrate the inversion approach, Figure 2 shows the algorithm for the case of $N_R = 3$ day^{-1}. In the following the accuracy of retrieval of R_2 data was computed as a function of the two parameters T_J and N_R.

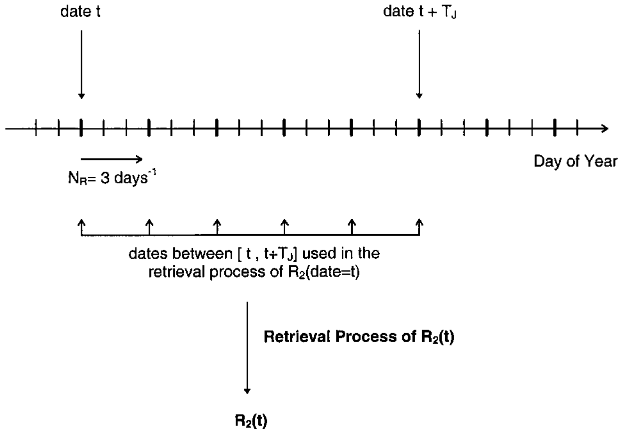

Figure 2. Retrieval algorithm for the case $N_R = 3$ day^{-1}.

4. Results and Discussion

4.1. Simulation Results

To check that the surface variables were estimated correctly, the ISBA simulations were tested against the data measured in 1989 and 1990. Since the calibration of ISBA, described in section 3.2, was based on the 1990 data set, it was important to verify that this calibration was also valid for 1989.

First, the simulated and measured fluxes (R_n, H, L_E, and G_S) were compared in 1989. The results of the comparison are summarized in Table 3, in terms of rms error and bias between measured and simulated values. As in 1990 the rms error in 1989 was relatively similar for the different components (R_n, H, L_E, and G_S) and varied from ~30 to 43 W m^{-2}. The values of the bias were slightly higher in 1989 than in 1990. In particular, the model overestimated sensible heat flux H and underestimated evapotranspiration flux L_E. These errors affecting the simulations of H and L_E were also obtained in 1990, although they were smaller. When the minimal stomatal resistance $r_{S\min}$ was computed by minimizing the cost function C_F, given by (12), the obtained values were $r_{S\min} = 211.4$ s m^{-1} and $C_F = 35.3$ W m^{-2} for 1989. These values were very close to those obtained in 1990. Therefore, in terms of flux density it seems that the calibration of ISBA performed in 1990 is also valid for 1989.

Second, the field hydrological characteristics were analyzed. Simulations of near-surface soil moisture w_G and soil reservoir R_2 were compared with the data measured in 1990 (Figures 1 and 3) and in 1989 (Figures 4a and 4b). The rms error and mean bias between measured and simulated values of w_G and R_2 are given in Table 4 for 1989 and 1990. In section 3.1 we observed that there was good agreement between observed and simulated soil moisture values for 1990. Using the same model calibration, Figure 4a illustrates that the time variations of w_G were also effectively reproduced in the 1989 data set.

Using a measured data point to initialize soil reservoir R_2 ($R_2 = 403.0$ mm on DOY 209 in 1990; $R_2 = 391.3$ mm on DOY 200 in 1989), the time variations of R_2 were correctly simulated in 1990 and 1989. However, we observed a slight overestimation of soil reservoir at the end of the crop cycle both in 1990 and in 1989. This discrepancy may be related to the underestimation of soil evaporation fluxes. The overestimation of w_G during a cloudy period at the end of the crop cycle in 1990 (DOY 255–258) was in agreement with this hypothesis: simulated soil moisture w_G increased as a result of very low simulated evaporation fluxes which could not compensate for upward water transfer from the soil reservoir to the surface. A second discrepancy was noted: simulated water content R_2 immediately following rainfall or irrigation was slightly

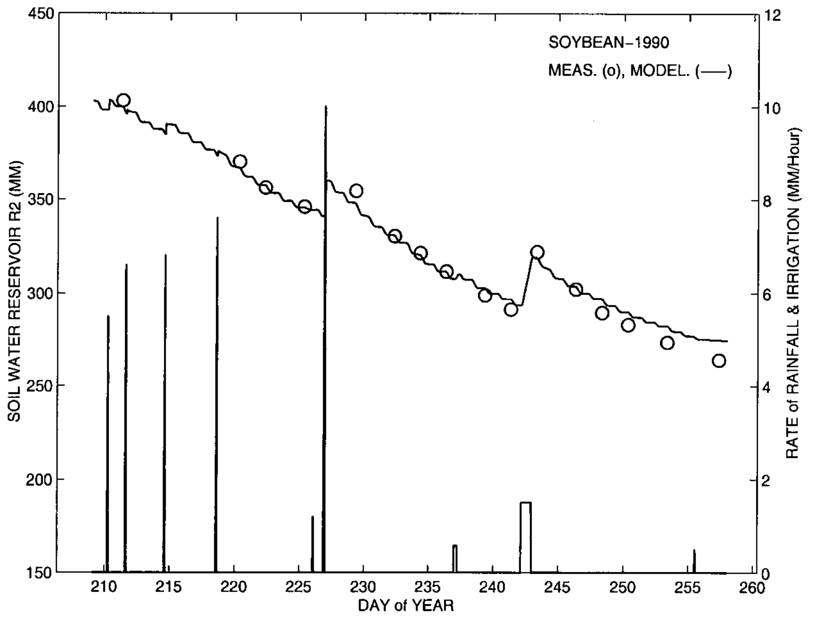

Figure 3. Comparison between measurements and simulations of soil water content in the root zone R_2 (mm) in 1990. The vertical bars represent the hourly rate of rainfall and irrigation (amount of water (mm) per hour).

lower than the observed values (Figures 3 and 4b). This discrepancy may be related to an overestimation of rainfall interception and/or deep water drainage. Except for these discrepancies, simulated soil moisture content at depth and at the surface was in good agreement with the experimental data both in 1989 and in 1990.

4.2. Retrieval of the Soil Reservoir

In contrast to section 4.1, in this section, soil reservoir R_2 was not initialized at the beginning of the crop cycle. By data assimilation in ISBA, soil reservoir at date *t* was retrieved daily from ground surface measurements of near-surface soil moisture w_G from date *t* to date $t + T_J$ (see section 3.3). This process was performed using the 1989 data set, while the 1990 data set was used to calibrate ISBA at the Avignon test site.

The data retrieval process was conducted for nine combinations of parameters T_J and N_R: three values of the integration period (T_J = 10, 15, or 20 days) were combined with three values of the measurement frequency (N_R = 1, 2, or 3 day^{-1}). The results are illustrated in Figure 5 for the four cases T_J = 20 days and N_R = 1 day^{-1} (Figure 5a), N_R = 2 day^{-1} (Figure 5b), and N_R = 3 day^{-1} (Figure 5c) and T_J = 10 days and N_R = 1 day^{-1} (Figure 5d). Figure 5a shows that with T_J = 20 days and N_R = 1 day^{-1} the retrieval process produced good estimates of the time variations in soil reservoir R_2 over the 60-day retrieval period. When the time frequency of the surface data included in the retrieval process was decreased to N_R = 3 day^{-1}, the retrieved values of R_2 were still good in terms of rms error and bias, but the time variations were slightly irregular (Figure 5c). Moreover, the results appeared to be significantly better using T_J = 20 days rather than T_J = 10 days (Figures 5a and 5d, for N_R = 1 day^{-1}).

The results of the whole data retrieval process are given in Table 5 and Figures 6a and 6b. Table 5 lists the rms error and the mean bias between measured and retrieved soil water reservoir R_2 as a function of the time period T_J (day) and the measurement frequency N_R (day^{-1}). In Figure 6a the rms error is displayed as a function of the integration period T_J for the three values of temporal frequency N_R (N_R = 1, 2, or 3 day^{-1}). The rms error decreased steadily when the integration period increased. It appears that rms error did not change significantly when T_J was increased beyond 20–30 days. However, beyond this range of variations for T_J the accuracy of retrieval is limited by the model accuracy in the simulations of hydrological characteristics. The rms error is sensitive to the value of N_R. In terms of retrieval error, a higher temporal frequency N_R partially compensates for a shorter period of integration. However, for a given number of surface measurements N_{mes} it seems preferable to use a long integration period rather than a high temporal frequency. For instance, for the given value N_{mes} = 10 a rms error of 25.2 mm was obtained for the retrieval configuration (T_J = 10 days and N_R = 1 day^{-1}; see Figure 5d), while the rms error was significantly lower (17.6 mm) for T_J = 20 days and N_R = 2 day^{-1} (Figure 5b).

The mean bias in the estimate of R_2 is presented in Figure 6b. The bias was small for the nine cases tested in this study (the maximum value of the bias, obtained for case T_J = 10 days and N_R = 2 day^{-1}, did not exceed 13.1 mm). The bias was found to be sensitive to the integration period T_J, and it decreased as T_J increased in an approximately linear fashion. In contrast to the results obtained for the rms error, the sensitivity of the bias to N_R was relatively small. Increasing N_R produced rather irregular daily variations in the retrieved R_2 value. However, when the retrievals were averaged over a short time period, a low bias was obtained for the estimates of R_2 for N_R = 2 or N_R = 3 day^{-1}.

5. Conclusion

Accurate measurements of soil moisture are needed for determining water exchange between the surface and the atmosphere, i.e., energy and water budgets and crop modeling. Passive microwave systems are very useful for characterizing soil moisture, which is highly variable, both spatially and tem-

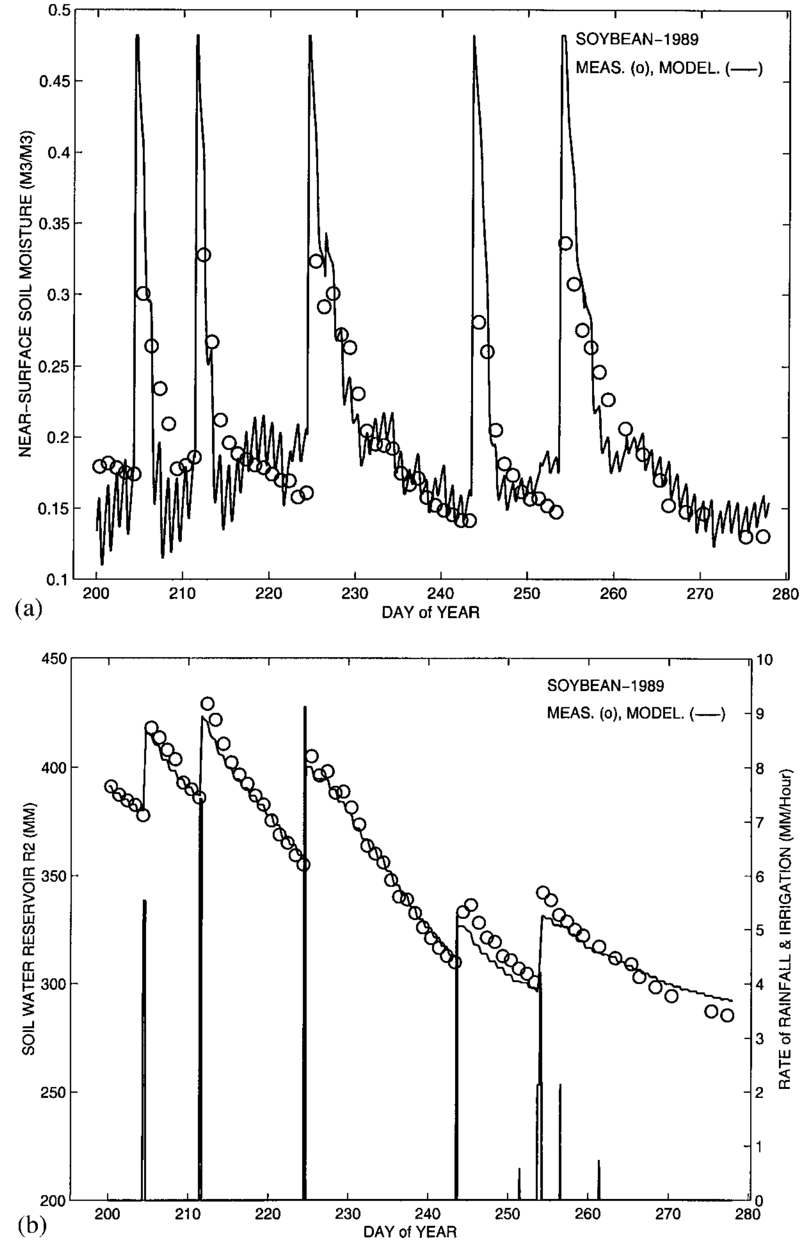

Figure 4. Comparison between measurements and simulations of (a) surface soil moisture w_G and (b) soil water content in the root zone R_2 (mm) in 1989. The vertical bars represent the hourly rate of rainfall and irrigation (amount of water (mm) per hour).

porally. However, the remote sensing (RS) estimates of soil moisture are limited to the soil surface (0–5 cm). Coupling the RS estimates of surface soil moisture with a SVAT model allows for the integration of surface estimates to accurately predict root zone soil moisture R_2.

On the basis of two data sets obtained with soybean crops (in 1989 and 1990) and using the ISBA model, this study investigated the requirements for using the remote sensing estimates of surface soil moisture to retrieve R_2. First, the simulations of ISBA were tested against the measured data in 1989 and 1990.

Table 4. Results of Direct Simulations: Comparison Between Measured and Simulated Surface Soil Moisture w_G and Soil Water Reservoir R_2 in 1989 and 1990

	Near-Surface Soil Moisture (0–5 cm) w_G, m^3 m^{-3}		Total Soil Water Content (0–1.3 m) R_2, mm	
	Root-Mean-Square Error	Bias	Root-Mean-Square Error	Bias
Soybean 1989	0.038	0.017	4.9	−1.3
Soybean 1990	0.033	0.011	5.2	1.6

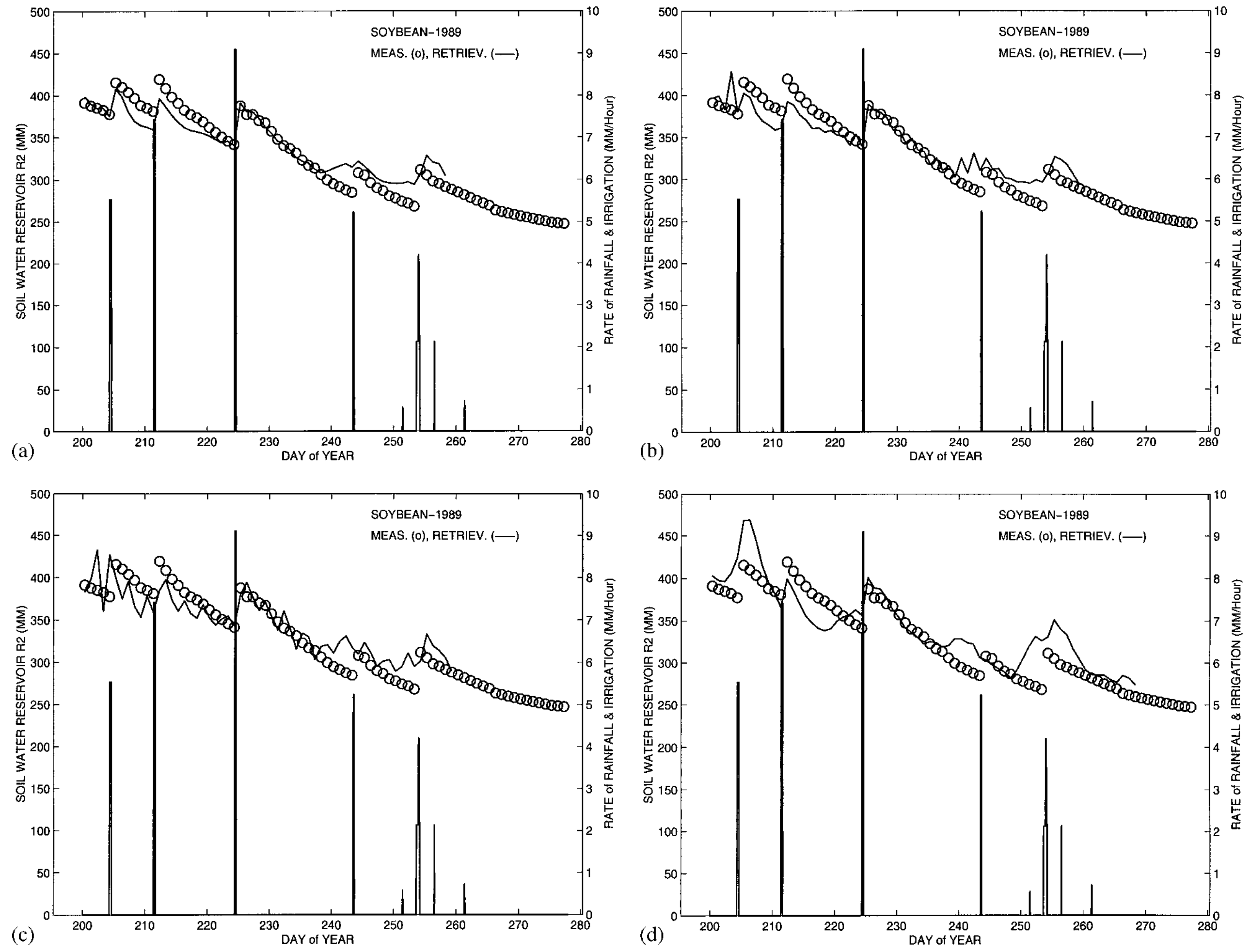

Figure 5. Comparison between measurements and retrievals of soil water content data in the root zone R_2 (mm) for several configurations of the data retrieval process: $T_J = 20$ days and (a) $N_R = 1$ day^{-1}, (b) $N_R = 2$ day^{-1}, and (c) $N_R = 3$ day^{-1}, and (d) $T_J = 10$ days and $N_R = 1$ day^{-1}. The vertical bars represent the hourly rate of rainfall and irrigation (amount of water (mm) per hour).

Results showed good agreement between measured and simulated fluxes and soil moisture values, both at the surface and at depth.

Then, the requirements for the use of surface soil moisture estimates in the retrieval process of R_2 data were investigated. The sensitivity of the retrieval process was measured for (1) time frequency and (2) integration period. The rms error in retrieved data decreased steadily when the integration period T_J was increased from 10 to 20 days but not after 30 days. For values of T_J >20–30 days the accuracy of retrieval was probably limited by the model accuracy in simulating hydrological characteristics. The retrieval process was less sensitive to the time frequency N_R than to the integration period (in particular, the bias was not very sensitive to N_R). Therefore, although a higher time frequency N_R can partially compensate for a shorter period of integration, for a given number of surface

Table 5. Results of Retrievals: Root-Mean-Square Error and Mean Bias Between Measured and Retrieved Soil Water Reservoir R_2 in 1989

Time Period* T_J, day	Measurement Frequency N_R, day^{-1}	Measurement Number N_{mes}	Root-Mean-Square Error on R_2, mm	Mean Bias on R_2, mm
10	1	10	25.2	10.4
9	2	5	29.4	13.1
10	3	4	30.7	13.0
15	1	15	19.1	5.0
15	2	8	20.3	5.6
13	3	5	25.0	7.9
20	1	20	15.6	0.7
19	2	10	17.6	2.1
19	3	7	20.9	3.0

*$T_J = N_R\,(N_{\text{mes}} - 1) + 1$.

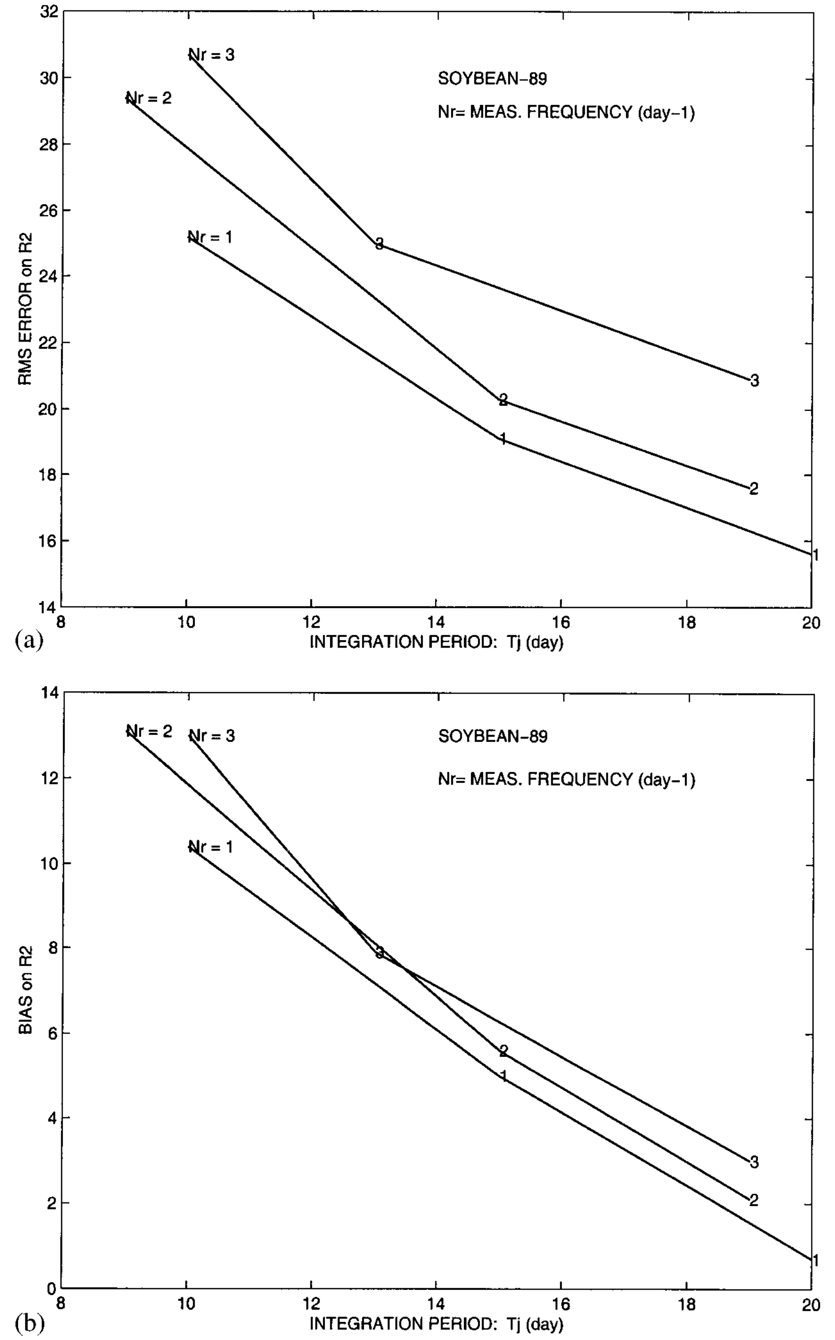

Figure 6. (a) Rms error and (b) bias between measurements and retrievals of soil water content data in the root zone R_2 (mm), computed over the whole crop cycle, as a function of the integration period T_J (day) and for three values of the measurement frequency N_R (day^{-1}).

measurements N_{mes} it is preferable to use a long integration period (i.e., 20 or 30 days). Furthermore, the value $N_R = 2$ or 3 days^{-1} was sufficient to provide good retrieval results.

In contrast to the study of *Calvet et al.* [1998] based on a short time period, in the present study it was necessary to normalize the simulations of surface soil moisture from the values of the soil parameters (wilting point w_{WILT} and field capacity W_{FC}). This normalization was found to be necessary to account for the vertical gradients of soil hydrological characteristics. The efficiency of the assimilation method was evaluated in this study. All the input parameters of ISBA used in the data retrieval process of the 1989 and 1990 data sets (Table 2) were obtained from ground measurements or from the literature. The only parameter which was calibrated was obtained from the 1990 data set, while the data assimilation process was based on the 1989 data set. This is a very positive result since it appears that once it has been calibrated for specific soil and vegetation characteristics, ISBA can be used for the data assimilation process, regardless of atmospheric forcing.

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