A GCM Experiment on Time Sampling for Remote Sensing of Near-Surface Soil Moisture

P. de Rosnay

Centre d’Etudes Spatiales de la Biosphère, Toulouse, France

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ABSTRACT

The use of microwave remote sensing opens new possibilities to study global soil moisture dynamics. The measured signal is proportional to the surface moisture and temperature of a thin soil layer. Several low-frequency microwave sensors, such as the Advanced Microwave Scanning Radiometer (AMSR) in C band and Soil Moisture and Ocean Salinity (SMOS) in L band, are now being flown (AMSR) or are scheduled to be launched in the near future (SMOS, in 2005) on sun-synchronous satellite platforms. Because of the diurnal cycle of the measured surface soil moisture content and its temporal variability, the restricted time sampling by an instrument in sun-synchronous orbit may be a source of error in the monthly mean quantities used for climate and land surface processes models. This paper presents a time sampling experiment, conducted with a general circulation model, in order to estimate the representativeness of the observations of the near-surface soil moisture, at a given time of the day, for the knowledge that can be gained of the monthly mean soil moisture. Due to the high temporal variability of the near-surface soil moisture, the impact of the revisit time of the satellite is shown to be critical for the estimated monthly mean soil moisture. This study emphasizes the requirement to develop and to use assimilation methods to produce meaningful soil moisture values from remotely sensed datasets.

1. Introduction

Soil moisture is a key component of the continental hydrological cycle and climatic system. Soil moisture content interacts with the atmosphere through the root water uptake and bare-soil evaporation, on various timescales on the order of hours for near-surface soil moisture (Raju et al. 1995), to interseasonal (Delworth and Manabe 1988) and interannual scales (Beljaars et al. 1996) for root-zone and deep soil moisture. The partitioning of energy between sensible and latent heat fluxes is linked to the seasonal variability of soil moisture, which influences the low-frequency atmospheric variability (Delworth and Manabe 1988; Shukla and Mintz 1982). Furthermore, Koster and Suarez (1995) emphasize the role of the land surface soil moisture condition for the prediction of precipitation. Milly and Dunne (1994) have shown that the land surface energy balance is strongly influenced by the soil moisture storage capacity. Resulting surface fluxes are distributed over large scales and affect the regional and continental atmospheric circulation (Beljaars et al. 1996; Polcher 1995).

The variations of soil moisture over small spatial and temporal scales is a major problem for monitoring large-scale soil moisture. Global observation of soil moisture does not exist at time- and space scales relevant for use in general circulation models (GCMs) or weather prediction models. However, the need for global-scale observation of soil moisture is clear for weather forecasting, climate modeling, soil hydrology, and water resources management (Walker and Houser 2001; Kerr et al. 2001; Njoku and Entekhabi 1996).

Over continental areas it has been established that the microwave emission at low frequencies (1.4 to 10 GHz) of the surface is very sensitive to the soil moisture content (Jackson et al. 1999; Wigneron et al. 1998; Schmugge 1983). But until today the development of passive microwave remote sensing of soil moisture from satellite was hindered by the low ground resolution of the passive microwave radiometers (Kerr et al. 2001). Recent technical improvements in the interferometric method opens the possibility to install low-frequency microwave sensors on satellite platforms. The Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) with a C-band channel was launched on the Earth Observing System (EOS) Aqua platform in May 2002. AMSR was launched on the Japanese Advanced Earth Observing Satellite-II (ADEOS-II) satellite in December 2002. Soil Moisture and Ocean Salinity (SMOS), with an L-band interferometer, is proposed for a launch in 2005 (Kerr et al. 2001). The aim of the SMOS project is to access information concerning the soil moisture and its dynamics over continental surfaces.
and to retrieve the ocean salinity over oceans. The ground
resolution has been selected to be between 27
and 50 km, the orbit is sun-synchronous with a local
time of acquisition at 0600 ascending and 1800 de-
scending. The repeat time varies between 1 and 3 days
depending on the latitude (Kerr et al. 2001).

L-band (1.4 GHz) is proved to be optimal to
determine the soil wetness (Wigneron et al. 1998). In contrast
to higher microwave frequency, the vegetation cover, if
not too heavy (below 5 kg m\(^{-2}\)), does not mask the soil
microwave emission of the surface. But remote sensing
remains limited to measurement of the top few centi-
meters at most of the soil moisture content. This thin
moisture layer interacts with the atmosphere on short
timescales and is highly variable both in space and time
(Raju et al. 1995).

In contrast, the climate and hydrological communities
are interested in the root-zone soil moisture content.
Calvet et al. (1998) have shown the feasibility of the
root-zone water content retrieval from a measurement
of surface soil moisture. The studies of Walker and
Houser (2001), Njoku and Entekhabi (1996), and Ent-	ekhabi et al. (1994) emphasize the fact that the develop-
ment and use of soil moisture obtained from remote
sensing data requires use of a sophisticated land surface
scheme with explicit representation of the vegetation,
and fine enough modeling of the soil moisture profile
dynamics. Moreover, the ground resolution of the soil
moisture observed from space is rather coarse. Each
pixel of the SMOS or AMSR satellite considers areas
of hundreds of kilometers square with a large diversity
of soil and vegetation types (Njoku and Entekhabi
1996). Thus land surface schemes used together with
remote-sensed soil moisture (for modeling and assimil-
ation) must take into account subgrid variabilities as
well as physical processes of soil–plant–atmosphere in-
teractions.

In spite of these difficulties, the future space missions
for soil moisture monitoring at the global scale will
allow us to access information on soil water content and
its dynamics at time and space scales consistent with
atmospheric processes. The resulting better knowledge
of soil moisture is expected to strongly improve our
understanding and the modeling of the coupling between
the continental water cycle and the atmosphere. In ad-
inition, a better knowledge of the initial soil moisture
conditions may improve the performances of the sea-
sonal meteorological prediction models.

Because of the time variability of the measured sur-
face soil moisture, the restricted time sampling by an
instrument in sun-synchronous orbit, for example,
SMOS or AMSR, may be a source of error in the monthly
mean quantities used for climate and land surface
models. If the variation in the diurnal cycle were ran-
dom, the daily or monthly products from a single sat-
ellite measurement with sparse time sampling would be
appropriate. But several studies show that in most re-
regions of the globe strong diurnal variations dominate
the meteorology and persist over several weeks (Haef-
felin et al. 1999). Thus, as shown by Haefelin et al.
1999 for the sun-synchronous ERBE (Earth Radiation
Budget) satellite, for solar-reflected and earth-emitted
radiation, the monthly estimates of a variable related to
meteorological conditions may be biased, even for per-
fect individual measurements.

In the present paper, a land surface scheme coupled
to a GCM is used to generate a synthetic “true” dataset,
from which surface soil moisture “observations” are
derived at different possible local times, and which will
be used to evaluate the results. The purpose of this paper
is not to analyze the simulated diurnal cycle of the soil
moisture, neither to estimate the periods of the land
surface variability, nor to find a method in order to
correct the time sampling error of the remote-sensed
soil moisture. Rather, our aim is to quantify at the global
scale how much a sparse temporal sampling, of the ob-
served surface soil moisture, affects the mean estimates
at the monthly and smaller timescales. This preliminary
analysis focuses on the time sampling error alone in the
theoretical case of a perfectly accurate measurement of
the surface soil moisture. The monitoring of surface soil
moisture by future space missions will be affected by
instrumental errors, uncertainties on different surface
characteristics (i.e., vegetation cover and soil roughness)
and large temporal variations on vegetation water con-
tent and surface temperatures. These sources of errors
are not analyzed here.

Despite some uncertainties in their simulated climate,
GCMs are currently the only tool which enables us to
do time sampling experiments at the global scale. The
physically based land surface scheme Schématisation
des Échanges Hydriques l’Interface entre la Biosphère
et l’Atmosphère (SECHIBA; de Rosnay et al. 2002;
Ducoudré et al. 1993) is used for this study. The fine
vertical soil discretization in this model allows the rep-
resentation of the time and space evolution of the surface
soil moisture that would be measured by a remote sens-
ing satellite. An original approach of subgrid-scale vari-
bility of vegetation and soil texture is taken into ac-
count to represent the surface heterogeneities in this
scheme. This allows us to simulate, at the grid cell scale,
a relevant soil moisture profile dynamic, which is shown
to be strongly related to the spatial variability of the
soil–plant systems (de Rosnay et al. 2002; de Rosnay
and Polcher 1998).

The next section presents the model and the numerical
experiment, section 3 is devoted to the analysis of the
GCM simulation and the impact of the time sampling
on the monthly mean estimates of soil moisture. Section
4 concludes.

2. Models and experiment

The present study is based on the analysis of a 1-yr
integration of the Laboratoire de Météorologie Dyna-
mique (LMD) GCM coupled to the land surface model

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SECHIBA (Ducoudré et al. 1993). The observed annual cycle of mean sea surface temperatures over the period 1978–88 is used as boundary conditions. Version cycle 6 of the LMD GCM is used here with a horizontal resolution of 96 points \( \times 72 \) points and 15 vertical levels in the atmosphere. The LMD GCM is documented in Polcher and Laval (1994), Le Treut and Li (1991), and Sadourny and Laval (1984). The time step of the model is 30 min.

a. Land surface scheme

1) DESCRIPTION

SECHIBA is used here to compute the land surface fluxes and the soil hydrology in the GCM. It was recently enhanced by the inclusion of the bare-soil hydrological model of the Centre for Water Resources Research of Dublin (Ireland) (de Rosnay et al. 2000; de Rosnay et al. 2002). The Fokker–Planck equation (Darcy’s Law, in the case of unsaturated one-dimensional groundwater flow in an isotropic and homogeneous soil, combined with the mass balance equation and expressed in terms of volumetric soil moisture) is used to compute the vertical soil water flow:

\[
\frac{\partial \theta(z, t)}{\partial t} = \frac{\partial}{\partial z} [D(\theta) \frac{\partial \theta(z, t)}{\partial z} - K(\theta)] - S(\theta),
\]

where \( \theta \) (\( m^3 \ \text{m}^{-1} \)) is the volumetric water content, \( K(\theta) \) (\( m^3 \ \text{m}^{-3} \ \text{s}^{-1} \)) is the hydraulic conductivity of the soil, \( S(\theta) \) (\( m^3 \ \text{m}^{-3} \ \text{s}^{-1} \)) is the sink term which represents the soil-water extraction by roots, \( z \) (m) is the vertical coordinate positive downward, \( t \) (s) is time, \( D(\theta) \) (\( m^2 \ \text{s}^{-1} \)) is the soil-water diffusivity.

The soil is assumed to be 2-m deep with 11 layers. The vertical grid spacing in the soil increases geometrically with depth downward, leading to a number of four layers in the top 2.15 cm of the soil column. De Rosnay et al. (2000) have shown that this choice of discretization of the soil in SECHIBA is an acceptable compromise between a detailed vertical resolution of the soil column and stability of calculated fluxes. The bottom boundary condition is taken to be a free-drainage condition, and the upper boundary condition depends on both the soil moisture at the surface and the atmospheric forcing. The van Genuchten–Mualem model is used to compute the relationship, for a given soil, between its hydraulic conductivity, volumetric water content, and matrix potential. It is widely used by the hydrological community because it agrees well with soil-water flux measurements and gives particularly good results near saturation. This formulation is suitable for large-scale modeling as it has been shown to be relevant for soil types with a large range of pore-size distribution (van Genuchten and Nielsen 1985).

The soil–plant interaction is based on the concept of soil moisture and root profile interactions, which allows us to represent the soil-water extraction variations in the vertical profile. The seasonal variation in the soil moisture profile influences the root-water uptake, which in turn affects the soil moisture vertical distribution (de Rosnay et al. 2002).

SECHIBA represents subgrid-scale variabilities of both vegetation and soil texture types by a tile approach to account for the surface heterogeneities. Up to eight vegetation types and three soil texture types are allowed for each grid box of the model. Each of them occupies a specified fraction of the surface of the mesh determined from Matthews (1984) and Zobler (1986) global-scale distributions. For each subgrid tile the land surface fluxes are computed independently. Mean fluxes for the grid cell are then computed from a weighted average of the subgrid fluxes. All the tiles for the box share the same atmospheric forcing.

De Rosnay et al. (2002) show that the combination of a fine vertical soil moisture profile with root profiles leads to a land surface scheme which is able to simulate complex physical processes of the soil–plant–atmosphere interaction at continental scales. Knowledge of soil type is critical for modeling the soil-water diffusion processes. The resulting fluxes and surface–atmosphere interactions are very sensitive to its representation. For a given vegetation type, and climate conditions, the computed transpiration may vary by a factor of 2 depending on the soil type. Moreover the depth of the root extraction varies seasonally and regionally, with shallow uptake during the rainy season and deep extraction in the dry season. The main features of the strong seasonal contrasts in the soil moisture profiles are well represented in the GCM. Despite some limitation in the availability of data about soil–plant distribution at global scale, it allows a physical representation of land surface processes and provides a platform for considering the diversity of the soil–plant–atmosphere interactions in climate modeling at continental scale.

In the context of large-scale studies for soil moisture remote sensing, SECHIBA is a suitable tool. The horizontal spatial scale, with subgrid variabilities of soil and vegetation types, is consistent with the ground resolution of soil moisture remote sensing (about 50 km). Due to the strong nonlinearities which characterize the soil moisture dynamics, the representation of different subgrid-scale contributions for the grid-cell-averaged soil moisture is critical for the relevance of the simulated soil moisture. Furthermore the time and space evolution of the soil moisture profiles are represented in the model with fine enough vertical resolution to simulate prognostic evolution of the observable from space surface soil moisture. The surface soil moisture, which is highly variable in space and time, is physically represented in interaction with vegetation cover and atmospheric processes. Such a land surface scheme allows the link of the scales of the satellite remote-sensed surface soil moisture, root-zone soil moisture, and atmospheric processes by a physical approach.
b. Numerical experiment

A 1-yr global-scale experiment is conducted with the LMD GCM coupled to the land surface scheme SECHIBA. The initial conditions of the model are those obtained after 2 yr of spinup, which was used previously by de Rosnay et al. (2002). This simulation allows us to generate synthetic mean daily soil moisture profiles considered as the “truth” over the land surfaces (averages based on the 48 time steps available each day). In addition, the simulated surface soil moisture is output twice every day to represent the surface soil moisture that would be measured by a virtual remote sensing satellite. Different cases of local time from 0600 to 2300 LT are studied (corresponding to the range of possible ascending and descending orbit that was considered for the future SMOS). But the analysis focuses on the retained 0600–1800 LT orbit for SMOS (Kerr et al. 2001). One of the interest of the selected SMOS orbit is to provide 0600 LT measurements of the land areas. At this hour, the soil and vegetation temperatures are similar, allowing thereby a simplification of the brightness temperature inversion. The inversion of the measurements at other hours of the day is more complicated. Since the temperatures of the soil and the vegetation are different, the inversion requires use of independent information on surface temperature. Our study allows to estimate how much the diurnal cycle of the measured variable at a given hour of the day affects the monthly mean estimates. Then to estimate the influence of the daily variability, the sensitivity to the revisit time is analyzed with sparser output (observations) of the model, every 2 days and every 3 days (the planned revisit time for SMOS varies between 1 and 3 days).

As shown in Fig. 1, the local time for data acquisition depends on the latitude belt. Thus the time sampling analysis presented here takes into account the latitude range according to Fig. 1 and the geographical distribution of the land surfaces over the earth. Two latitude belts are studied: between 40°S and 40°N the morning and evening local time for observation are identical (e.g., 0600–1800), and between 40° and 70°N, ascending and descending local time are nonsymmetric (e.g., 0600–2000).

3. Results of the global-scale time sampling experiment

Figure 2 shows the zonal averages over land surfaces of the root-mean-square (rms) of the relative difference between “estimated” and “true” surface soil moisture. According to the analysis of Wang (1987) and Raju et al. (1995), which show that the top 2.5 cm of the soil are appropriate to represent the sampling depth at L-band, four top soil layers (e.g., top 2.15 cm of the soil) are considered for this study. This figure considers the theoretical case with two (A.M. and P.M.) measurements every day. In January (top) the Southern Hemisphere is characterized by larger rms differences than the Northern Hemisphere. The larger rms difference associated with larger errors in the Southern Hemisphere are due to the fact that in the summer the diurnal cycle is accentuated by a stronger solar insolation during the daytime. The seasonal contrast between Northern and Southern Hemispheres is confirmed by the second panel, which indicates symmetric features for July. Larger rms differences in the Southern Hemisphere in January compared to the Northern Hemisphere in July are explained by the different repartition of continental surfaces in the
two hemispheres. The lower number of continental points in the Southern Hemisphere emphasizes the spatial variability and leads to a larger rms difference than in the Northern Hemisphere.

As shown by Fig. 2, the differences also depend on the local time of observation without any systematic dependence on latitude. This points out that the strong diurnal cycle of the surface soil moisture leads to a sensitivity of the monthly mean estimates to the precise local time for acquisitions. In general, lower rms differences are shown for 0600–1800 LT observations, compared to larger rms for 0900–2100 LT acquisition, but not at all latitudes. But the rms differences only vary in a range of about 1% depending on the local time of acquisition. The influence of the local time is important in regards to the time sampling error, which remains very low in this experiment, below 2%. However it is rather tricky to point out, from a GCM experiment, a suitable precise local time for acquisition of surface soil moisture as the simulated diurnal cycle over land surfaces by GCMs is shown to be shifted as compared to observations. The maximum precipitation is shown to occur several hours too early (Guichard and Petch 2001; Redelsperger 2001).

Figure 2 shows that the rms values of the relative differences remains below 1% in winter hemisphere and varies between 1.0% and 1.9% in the summer hemisphere. An analysis of the ascending (A.M.) and descending (P.M.) measurements indicates that this pair of measurements leads to a minimization of the errors on the estimated averaged values (not shown). The morning time sampling error is mainly compensated by evening error (with opposite sign). This set of two acquisitions allows the capture of the mean daily values of soil moisture despite its diurnal cycle.

This good agreement between estimated monthly soil moisture, from two daily observations, and simulated
true soil moisture is shown in the Fig. 3 both for the Tropics and for the midlatitudes. This global-scale analysis clearly indicates that two daily observations of the surface soil moisture is relevant to produce accurate estimates of the surface soil moisture on larger timescales.

The previous analysis focused on daily observations of soil moisture in the LMD GCM. The time sampling of the future satellites for remote sensing of the surface soil moisture will allow 1 to 3 days for temporal sampling depending on the latitude. While the relevance of measurements with 1-day revisit time is influenced by the shape of the diurnal cycle of the measured variable a sparser time sampling will be influenced by its synoptic variability. In particular, some studies have emphasized at regional scales the role of the 3–5-day variability of the rainfall over West Africa (Taylor and Clark 2001). They indicate that the diurnal forcing of the incoming solar radiation is shown to be transferred through the land surface properties from the diurnal to synoptic scales (Taylor and Clark 2001; Gash et al. 1997).

The deterioration of the estimated monthly soil moisture from 1 to 3 days observations is assessed below. The results of two measurements every second day and every third day are presented in Figs. 4 to 6.

Figure 4 shows that the agreement between the simulated estimated and true monthly mean soil moisture, is lower for every third day than for every 2-day and every day measurements (Fig. 3). The reduction in the frequency of the data acquisition leads to an increased error. The results shown here for January are representative of the time sampling error for the other months, with a smaller scatter for the midlatitude belt.

The zonal rms of the relative error on soil moisture for the 40°N–40°S latitude belt is shown in Fig. 5 for
January and July. As for every day acquisitions, every second day and every third day outputs of the model indicate a similar sensitivity to the time sampling in midlatitudes (not shown) rather than in the Tropics. Figures 2 and 5 clearly show that the rms of the errors strongly increases when the time sampling of the remotely sensed soil moisture is sparser. While the rms was limited to 1.9% for every day acquisition (Fig. 2), it reaches 7% in the summer hemisphere, and stays above 2% in the winter hemisphere for every two-day acquisitions. A 3-day frequency of data acquisition leads to increase further the zonal rms of the errors, up to 11%, as shown in Fig. 5. It appears from Fig. 5 that the precise local time for acquisition has a rather low influence on the rms of the error compared to the value of the rms itself. As observed with daily acquisition, there is no agreement between the rms values of the summer hemisphere for the 2 months. The increase in the time sampling error when frequency of the observations decreases is explained by the temporal variability of the surface soil moisture during the interval. This indicates that a 2- or 3-day repeat time for the measurement of the surface soil moisture does not allow us to capture the day-to-day variability simulated in the GCM.

Figure 6 gives the geographical distribution of the relative error on the monthly mean estimates of the surface soil moisture in January and July, for a 2- and 3-day repeat time. The maximum value of the rms difference at 30°S in Fig. 5 for January is explained by strong errors in South America and Australia with high spatial variability of the errors. In the Northern Hemisphere, strong rms differences shown in Fig. 5 at 30°N for January are also explained by longitudinal differences in relative error of the monthly mean estimates. These longitudinal differences result from regional differences in the timescale of the meteorological variability in the model. Figure 6 shows that the absolute
value of the relative error on the monthly mean estimates is above 2% in a large number of regions, and larger than 10% in some regions. But while the maximum values of the errors are limited to 22% for a 2-day repeat time of the observations, they reach about 60% in some regions when the time sampling is degraded to 3 days. These time sampling errors (for two acquisitions every 3 days) are very large. They are caused by the too-sparse time sampling for the observation of the surface soil moisture, which is characterized by high day-to-day variability. This analysis suggests that due to the high time variability of the near-surface soil moisture, the repeat time of the satellites is critical for the soil moisture remote sensing.

In the earlier analysis, the time sampling error may be underestimated as compared to a real satellite which will allow at most one measurement per day, with alternation between A.M. and P.M. acquisitions. In addition, the analysis of the errors is conducted here only for the monthly mean estimates of soil moisture (mainly restricted to the purpose of the climate application). Estimates over smaller timescales are expected to be associated with larger rms of the errors.

Figure 7 shows the relation between observed and estimated soil moisture based on only one observation at the time of the satellite overpass every 3 days for (a) the monthly mean soil moisture in January, and (b) a 2-week-mean soil moisture in January. This figure indicates that the loss of information from two acquisitions (A.M. and P.M.) to only one acquisition (A.M. or P.M.) every 3 days increases further the errors in the estimated soil moisture. In addition, estimates of soil moisture over smaller time periods, more relevant for hydrological and water resources management applications, are shown to be associated with larger errors than monthly averages. Figure 8 allows us to capture the geographical features of the soil moisture estimates' errors in the case of realistic orbit characteristics, from monthly to two-week time windows. The main impact of the degradation of the time sampling from 2 to 3 days was shown earlier to be an increase in the errors' values (Fig. 6) in the regions already affected by sampling errors. It appears now that the decrease to only one observation (instead of two) every 3 days leads to an increase in the geographical extent of regions affected by strong errors. In this configuration of the data...
acquisition, corresponding to the orbit design of the soil moisture remote sensing satellites, the monthly mean errors in the estimated soil moisture are very large. For smaller windows than monthly, the errors are enhanced further and large regions are affected by errors (in the estimated soil moisture) above 18%. Regarding the high values of the errors depicted in Fig. 8 (right), it is clear that smaller time windows would be not suitable to represent the mean values of the surface soil moisture from remote sensing alone. This sensitivity of the errors to the time sampling and to the period length of the average is a consequence of the very high time variability of the surface soil moisture. The quantitative results presented here point out that the use of the remote-sensed surface soil moisture measurements require development of sophisticated inversion methods to interpolate the soil moisture between the acquisitions.

4. Conclusions

This paper addresses the question of time sampling error on the estimated monthly mean surface soil moisture from the remote-sensed soil moisture by future low-frequency passive microwave sensors on satellites. These sun-synchronous satellites will allow at most one acquisition per day of the surface soil moisture (top few centimeters). The upper few centimeters of the soil are the most exposed to the atmosphere, and their soil moisture varies rapidly in response to rainfall and evaporation, from diurnal to synoptic scales (Walker and Houser 2001).

We use a GCM experiment to generate both synthetic “true” near-surface soil moisture, and “observed” surface soil moisture that would be measured by a remote sensing satellite. Different local time and repeat time of the satellite measurements are tested. The purpose is not to influence the orbital definition of these future satellites (the chosen sun-synchronous orbits result from strong technical and scientific constraints). The aim is to evaluate, with a GCM, the error on the monthly mean estimates of the surface soil moisture depending on the revisit time of a sun-synchronous satellite.

The first part of the study analyses the idealized case of two daily observations of the soil moisture. In this case the rms errors on the monthly estimates are shown to be less than 2%. Such a high frequency for measurement of the soil moisture enables the capture of the mean daily soil moisture values and gives accurate estimates of the monthly mean. In this case the sensitivity to the precise local time for the acquisition is shown to be in the range of 1%.

However, the satellite remote sensing of the surface soil moisture does not allow such a high repeat time. In many regions, at most one observation every 2 or 3 days will be possible. The theoretical cases of two acquisitions every 2 days and every 3 days are analyzed here from the GCM outputs. They show that the strong day-to-day variability of the measured soil moisture leads to a drastic increase in the errors of the resulting monthly mean estimates of the soil moisture when the frequency of acquisition decreases from 1 to 3 days. For sparse observations, the local time for the observation is shown to have a very small impact compared to the revisit time (Fig. 5). Then the influence of the only one measurement (A.M. or P.M.) every 3 days is shown (Figs. 7 and 8). This configuration of the data acquisition mimics the future satellite orbit in most of regions with 3 days as repeat time (ascending 1 day, descending 3 days after). The time sampling errors on the estimated soil moisture is shown to be very large in many regions of the world for this more realistic orbit design. Figure 8 shows that the errors are enhanced further, up to 70% in many regions, when the considered timescale for averages is reduced from the month to 2 weeks.

The results presented in this paper must be considered with care because of the large uncertainties associated with the simulated climate by GCMs. In particular, the
deep convection simulated in climate models is shown to occur several hours too early in most GCMs (Guichard and Petch 2001; Redelsperger 2001). However, the quality and relevance of GCMs were strongly improved in the last decade. Today most GCMs are recognized as being able to capture the main feature of the climate system. Despite some uncertainties, the diurnal to interseasonal and interannual variabilities are represented (Taylor and Clark 2001; Beljaars et al. 1996; Harzallah et al. 1996; Vinnikov et al. 1996; Koster and Suarez 1995; Delworth and Manabe 1988). Moreover despite some uncertainties in their simulated climate, GCMs are the only tool that allows us to study the time sampling experiments at the global scale.

The present study considers the case of a perfect measurement of soil moisture. The real satellite remote sensing of soil moisture will be affected by instrumental errors (expected to be low), and the soil moisture retrieval will be affected by uncertainties of surface temperature, vegetation, and soil characteristics. The strong heterogeneity of the measured surface soil moisture will also make the remote sensing of soil moisture difficult at a spatial scale of several kilometers. Thus the soil moisture remote sensing is very complex and this preliminary paper only addresses the question of the impact of the time sampling on the estimated monthly mean soil moisture. Further analysis must be conducted in order to estimate the impact of the diurnal cycle of the surface temperature (expected to be large) on the time sampling error. To address this topic at a global scale it is necessary to make the coupling between a global land surface scheme and a microwave emission model to generate and analyze values of the surface brightness temperature as seen from space (Pellarin et al. 2002; de Rosnay and Schmugge 2001, unpublished manuscript).

This theoretical global study shows that the high time-variability of the surface soil moisture, that will be remotely sensed from space, causes problems in the estimation of the monthly (and smaller timescales) mean estimates of soil moisture. Even for every second-day revisit time, the time sampling error is more than twice the time sampling error resulting from daily observa-
tions. An approach to access the soil-water dynamics at smaller timescales than the space remote-sensed data of soil moisture, is to develop the use of assimilation methods in land surface schemes. This ensemble of methods consists of updating the land surface schemes by assimilating data, to minimize the effect of models' and data errors. It is well adapted to the remote sensing of the variable with higher time variability by allowing relative independence to the time sampling. Several studies show that the development of assimilation methods of L-band brightness temperature for soil moisture retrieval is as suitable for hourly revisit time as for 3-day interval (Galanowitz et al. 1999; Entekhabi et al. 1994). Assimilation of near-surface soil moisture with a Kalman scheme is also shown to be relevant for the soil moisture profile retrieval with a 5-day revisit time (Walker et al. 2001). Moreover assimilation methods will allow us to account for the short timescale processes that would influence the measurement of the microwave brightness temperature (e.g., the dew deposition). It is also relevant to be used for climate and hydrological studies as it affords a link between surface (observed) and root-zone soil moisture.

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