Assimilation of Land Surface Variables for Model Initialisation at Météo-France

Christoph Rüdiger[a], Jean-Christophe Calvet[a], Jean-François Mahfouf[a], Lionel Jarlan[b,c], Gianpaolo Balsamo[d], and Joaquin Muñoz Sabater[a,e]

[a]Météo France, Centre National de Recherches Météorologiques (CNRM/GAME), URA CNRS 1357, Toulouse, France
[b]Centre d'Etude Spatiale de la Biosphère (Cesbio), Toulouse, France
[c]Institut de Recherche pour le Développement (IRD), Toulouse, France
[d]European Centre for Medium-Range Weather Forecasting (ECMWF), Reading, United Kingdom
[e]Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS), Toulouse, France

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EXTENDED ABSTRACT

The aim of this study is the preparation and test of an offline Land Data Assimilation System (LDAS) for the initialisation of the prognostic variables of the land surface model ISBA (Interactions between the Soil, Biosphere and Atmosphere) used at Météo-France for various applications (weather prediction, hydrological studies, land carbon monitoring). This system is based on a simplified 2D-VAR assimilation scheme, which allows computing the Jacobians of the observation operator in a computationally inexpensive way. Two different sets of data can be assimilated: i) remotely sensed leaf area index (LAI) and surface soil moisture, and ii) relative humidity and temperature at 2m from the synoptic observational surface network. The various prognostic variables that can be analysed. are the root zone soil moisture the vegetation biomass and soil temperature

A further aspect of this study is the production of SMOS-type brightness temperatures to evaluate the possibility and potential problems of the assimilation of multi-angular microwave observations to constrain the model behaviour

Results from a preliminary study are presented for the period 2001-2004 over the SMOSREX (Surface Monitoring Of Soil Reservoir EXperiment) experimental site located in south-western France. While the year 2001 represents an average year in terms of climatic conditions, the region underwent a severe drought during the summer of 2003. During this period, observed root zone soil moisture fell below the wilting point. These varying climatic conditions allow evaluating the potential of the assimilation system during extreme events. Indeed, initial results have shown that the joint assimilation of LAI and surface soil moisture lead to a significant improvement of the general representation of root zone soil moisture and vegetation biomass.

The simplified 2D-VAR will be initially included into the operational model platform SURFEX (SURFace EXternalisée) of Météo-France. However, the conceptual design of this assimilation scheme will make it possible to transfer it to other platforms at other institutions.

Two preliminary studies undertaken at Météo-France which make use of this conceptual LDAS-model set-up are being reviewed. It is shown that the simplified 2D-VAR presented here has the potential to quickly retrieve accurate model states.

1. INTRODUCTION

For climate research and numerical weather prediction, (hydrological) land surface models require an accurate representation of the land surface processes (plant transpiration, response to atmospheric CO_2 concentration, soil hydrology, etc.). In particular, the soil moisture content plays an important role, as it regulates the latent and sensible heat exchange between the land surface and the atmosphere (Entekhabi et al., 1996, Dirmeyer et al., 1999). Moreover, it controls the partitioning of precipitation between infiltration water and surface runoff. Because of the lack of homogeneous observation networks and the high spatial variability of soil moisture, only models are able to provide information at sufficiently high resolutions. However, those models are only approximations of real physical processes in the soil and the atmosphere. Indeed, they contain assumptions on the described physical processes and uncertainties in the specification of parameters, which result in errors in the simulations. To overcome this limitation, hydrological and near-surface in-situ (if available), and Earth Observation (EO) data can be used to control the quality of the representation of the land surface processes, by constraining the model performance through data assimilation.

In the past, work has been undertaken in the assimilation of remotely sensed or in-situ observations (Mahfouf, 1991; Entekhabi et al., 1994; Walker et al., 2001; Reichle et al., 2001; Balsamo et al., 2004 & 2006) to constrain the soil moisture predictions in land surface models. At Météo-France, an offline data assimilation system is currently under development using the ISBA-A-gs model (Interactions between the Soil, Biosphere and Atmosphere; A-gs – model option with calculation of the stomatal conductance) and a simplified 2D-VAR assimilation algorithm This system will allow the assimilation of different observations either individually or jointly, for the analysis of soil and vegetation variables

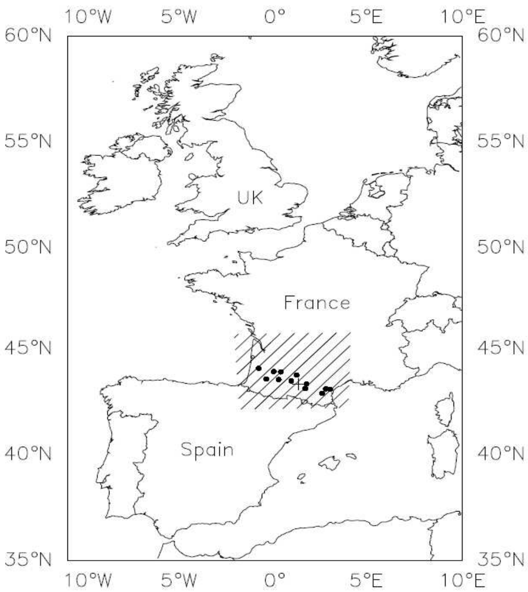

Figure 1. Location of the focus area in south-western France (shaded), the 12 SMOSMANIA sites (dots), and the SMOSREX site near Toulouse (+).

The ISBA-A-gs model, developed at Météo-France, (Calvet et al. 1998-2004, Gibelin et al. 2006) permits to simulate the water and carbon fluxes over land, together with the corresponding soil moisture and vegetation biomass. It has been included in the future operational platform SURFEX (SURFace EXternaliséé) of Météo-France for applications in hydrology, meteorology and climate modelling.

A simplified 2D-VAR algorithm (Balsamo et al. 2004) has been incorporated into ISBA by Munoz-Sabater et al. (2007ab), for the assimilation of biomass and soil moisture sensitive EO data at the same time. The assimilation scheme is currently extended to allow for the use of relative humidity and air temperature at 2m, obtained from a surface analysis of SYNOP (synoptic observational surface network) observations. This work is based on the feasibility study of Mahfouf (1991) and on operational implementations in various weather centers (Météo-France, ECMWF, Environment Canada).

In the present paper, the general definition of the assimilation scheme is presented Then the preparatory work currently underway to support the required tests and validation of the assimilation scheme is presented. Finally, some preliminary results from two different studies are briefly reviewed to illustrate the potential of the assimilation scheme.

2. THE SIMPLIFIED 2D-VAR

Variational assimilation methods combine information of observations within a time window of predefined length and an a-priori (background) model state to define an optimal model. This optimal state, taking into consideration the model (or background) and observational errors is found through the minimization of an objective function *J*. In case of the simplified 2D-VAR this objective function is defined as

$$J(\mathbf{x}) = \frac{1}{2}\left(\mathbf{x}-\mathbf{x}^b\right)^T \mathbf{B}^{-1}\left(\mathbf{x}-\mathbf{x}^b\right) + \\ + \frac{1}{2}\left(\mathbf{y}-H(\mathbf{x})\right)^T \mathbf{R}^{-1}\left(\mathbf{y}-H(\mathbf{x})\right), \quad (1)$$

where $\mathbf{x}$ is the predicted model state; $\mathbf{x}^b$ is the a-priori (background) model state, $\mathbf{B}$ is the background error covariance matrix; $\mathbf{y}$ the observed variables; H an observation operator, which projects the model state in the observation space; and $\mathbf{R}$ is the observation error covariance matrix.

In the general definition of (1), H is a non-linear observation operator, and the minimum of J has to be found through an iterative process. In the present simplified 2D-VAR, it is assumed that this operator can be linearized, and its Jacobian is determined through a simple perturbation $\delta\mathbf{x}$ of the model state $\mathbf{x}$:

$$\mathbf{H} = \frac{\delta\mathbf{y}}{\delta\mathbf{x}}, \quad (2)$$

where $\delta\mathbf{y}$ is the change in the observation variable $\mathbf{y}$, due to the perturbation of the model state $\mathbf{x}$ ($\delta\mathbf{x}$). The analysed state $\mathbf{x}^a$ is given by :

$$\mathbf{x}^a = \mathbf{x}^b + \mathbf{K}\left(\mathbf{y}-\mathbf{H}\left(\mathbf{x}^b\right)\right), \quad (3)$$

where $\mathbf{K}$ is the gain matrix, which is given by the expression

$$\mathbf{K} = \mathbf{B}\mathbf{H}^T\left(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\right)^{-1}. \quad (4)$$

3. APPLICATIONS AT MÉTÉO-FRANCE

3.1. Study Area

To test the assimilation of the future Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2001) brightness temperatures (Tb) and to validate the soil moisture products derived from SMOS and other sensors (e.g. from the Advanced Scaterrometer (ASCAT)), field experiments and modelling activities are conducted over south-western France. The catchment chosen is the Adour-Garonne basin in south-western France, which extends from 2°W to 4°E, and 42.5°N to 46°N (Fig. 1). This catchment is particularly suited for a study such as it is presented in this paper, due to its diverse surface characteristics with agricultural plains in the central region, dense forests in the west, grasslands in the Massif Central in the east, and the mountainous regions of the Pyrenees in the south. This configuration of surface conditions allows to study the potential of the assimilation scheme for various climatological and biophysical situations. Moreover, a network of in-situ soil moisture stations, providing real-time observations (SMOSMANIA – Soil Moisture Observing System: Meteorological Automatic Network Integrated Application) has been implemented in this area (Fig. 1).

3.2. Simulation of synthetic brightness temperatures

A synthetic L-band brightness temperature (Tb) data set was built for the period 2000-2005. Over this period, SPOT/VGT and MODIS LAI products are available. For the preparation of the operation of the SMOS mission it is important to understand the relationship between soil moisture conditions on the ground and L-band observations from space. For this purpose, ISBA-A-gs was run for a period of 5 years (January 2000 – July 2005) in order to obtain long-term land surface data sets, required to produce synthetic brightness temperature fields for the simulation of SMOS synthesised FOVs. The land surface data was used as input into the L-band Microwave Emission Model for the Biosphere (L-MEB, Wigneron et al. 2007), to produce brightness temperatures at 8km resolution over south-western France. LAI estimates are produced by the model and are fully consistent with the synthetic Tb. They can be compared with EO derived estimates (MODIS and SPOT/VGT), available for the same period.

3.3. Soil moisture observational network

SMOSMANIA implements soil moisture measurements in a portion of the automatic ground station network of Météo-France (the RADOME network – Réseau d'Acquisition de Données et d'Observations Météorologiques Etendues). The SMOSMANIA network permits to monitor soil moisture in south-western France thanks to automatic, real-time in-situ measurements of soil moisture and soil temperature profiles (-5, -10, -20, -30 cm). The soil moisture measurements are obtained with horizontally installed ThetaProbes. Twelve ground stations were installed in 2006 allowing to observe the hydrologic and climate gradient between the Mediterranean and the Atlantic. The soil moisture data acquisition has been fully operational since January 2007. In 2007, soil temperature probes were installed and the calibration of the soil moisture probes was finalized. Several objectives are considered: i) validation of the operational soil moisture products of Météo-France (http://www.eaufrance.fr), produced by the hydro-meteorological model SIM (Habets et al. 2005); ii) validation of new versions of the land surface model of Météo-France; iii) contribution to the calibration and validation campaigns of future SMOS products (surface soil moisture) and other space-borne remotely sensed soil moisture products; iv) help to implement the assimilation of SMOS data and verify the analysed variable (root-zone soil moisture), v) ground-truthing of future airborne SMOS CAL/VAL campaigns .

The combination of these different campaigns and studies over the same region allow a first synthetic study, before real-time observations will become available (the launch of SMOS is set for mid-2008, and the SMOSMANIA network will be fully operational by the end of 2007).

4. PRELIMINARY RESULTS

4.1. Assimilation of surface soil moisture and LAI

The simplified 2D-VAR was tested in a study, which was focussed on a single site: the SMOSREX experimental site (Surface Monitoring Of Soil Reservoir Experiment; De Rosnay et al., 2006), located in south-western France (Fig. 1). In Muñoz et al. (2007ab), surface soil moisture (w_g) observations were assimilated every 3 days with an 10-day assimilation window using four different assimilation schemes. The simplified 2D-VAR method demonstrated to be the most suitable for an implementation in an operational configuration (best compromise between computational cost and accuracy of the retrieved states). The results for the root-zone soil moisture (w_2) analyses were generally satisfactory, with ISBA-A-gs using a prescribed LAI obtained from in-situ measurements (Muñoz et al., 2007a). In Muñoz et al. (2007b), a step forward was made, and the LAI was simulated by the surface scheme using the parameterization for the plant photosynthesis and the vegetation growing and senescence phases of ISBA-A-gs (Gibelin et al. 2006). Consequently, both w_2 and vegetation biomass could be jointly analysed (Fig. 2) through the assimilation of LAI and w_g observations from the SMOSREX experimental site.

The results show a significant improvement of the representation of the vegetation, even with a

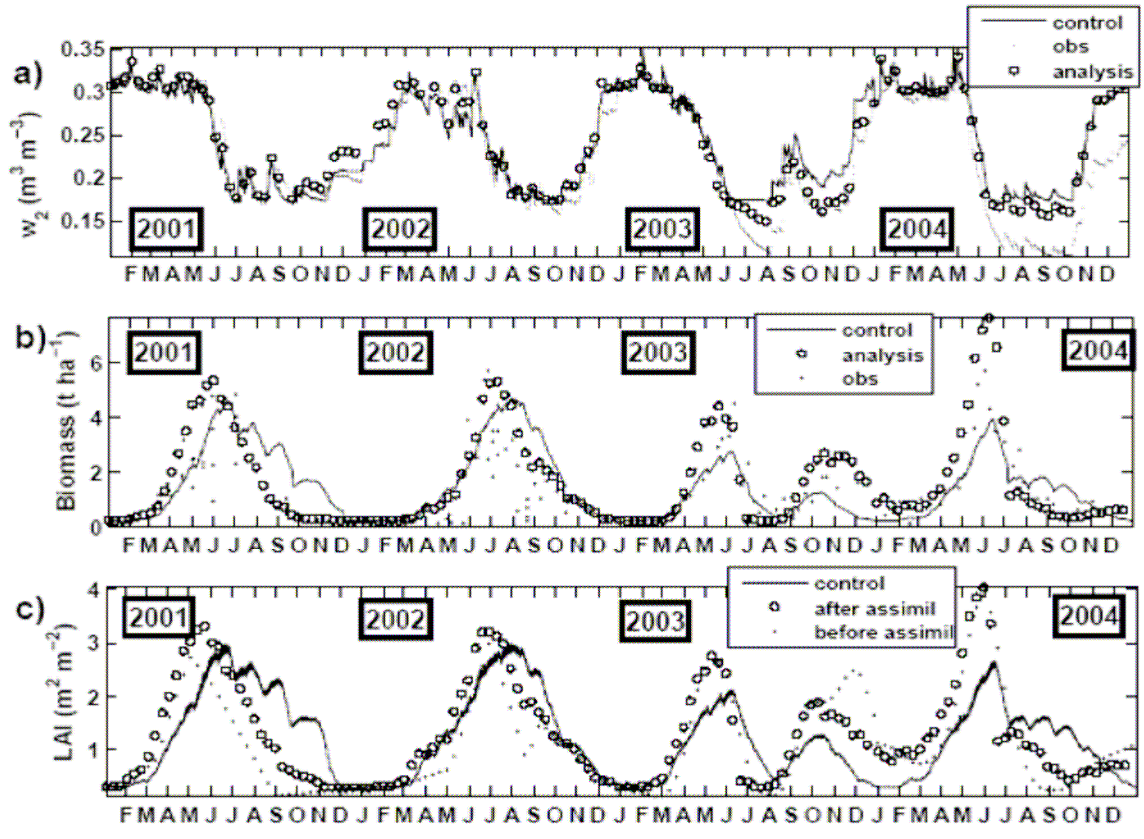

Figure 2. Analysis of a) the root zone soil moisture (circles) and b) vegetation biomass, using a simplified 1D-VAR method from 2001 to 2004 over the SMOSREX experimental site. c) LAI before and after the assimilation. For comparison purposes, analysed values are superimposed over the in-situ observations (points) and the model basic estimations (solid line). Reproduced from Muñoz et al. (2007b).

correction of the temporal drift in the vegetation biomass and LAI. The surface soil moisture is also corrected, in particular the error overestimation of the soil moisture content in the very dry summers of 2003 and 2004. (Fig. 2).

4.2. Assimilation of screen-level observations and surface soil moisture

A combined 2D-VAR assimilation of temperature and relative humidity at two meters above ground (T2m, HU2m) with superficial soil moisture that could be retrieved from a satellite instrument (wg) has been tested in a "twin experiment" framework (Mahfouf, 2007). A month of forcing data has been extracted from the ECMWF reanalysis ERA40 for a grassland site over US in July 2002. Simulated observations were generated from a reference run starting from a saturated soil. An "open loop" simulation has been initialized with a dry soil (at wilting point) and the precipitation forcing is divided by a factor of two. Assimilation experiments start at the wilting point and are expected to get closer to the reference simulation.

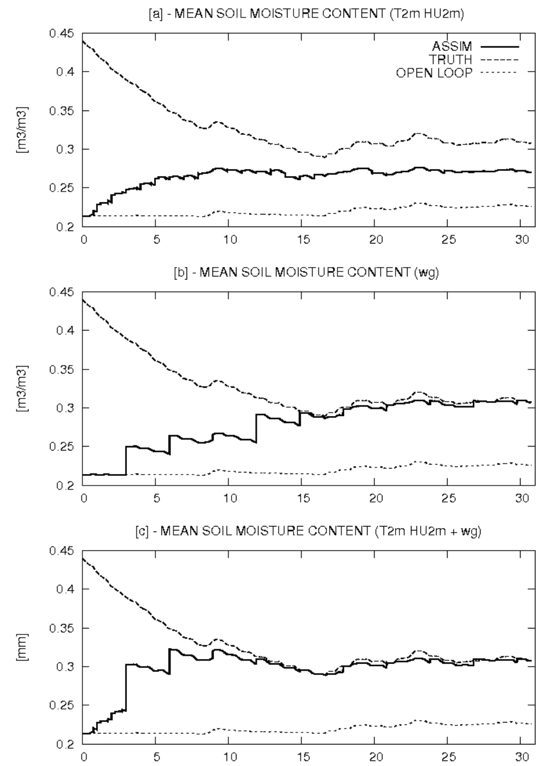

Figure 3. Evolution of root zone soil moisture (July 2002 US prairie site) during 2D-VAR assimilations (ASSIM) considering screen-level observations (a), surface soil moisture observations (b) and both (c). Observations are produced by the reference simulation (REF) and the open loop (OL) run does not assimilate observations (from Mahfouf, 2007).

In a first experiment, T2m and HU2m are assimilated every 6 hours. Results for the root-zone soil moisture content (Fig. 3a), show a rapid convergence from a very dry initial value to amounts around 0.27 m3/m3 after 10 days which is close to the field capacity for the chosen soil type. Indeed, screen level parameters are modified through the partition of the turbulent fluxes between sensible and latent heat fluxes. Above field capacity, surface evapotranspiration takes place at potential rate and is not sensitive to soil moisture anymore. The 2D-VAR assimilation of wg every 3 days shows a convergence towards the reference value after 12 days (Fig. 3b). Here, the link between the observation wg and the control variable takes place through soil diffusion processes (water potential gradients) that are not limited by the field capacity value. Finally, the combined assimilation of T2m, HU2m and wg is displayed in Figure 3c. The final result is better than each individual assimilation. In particular, soil corrections are possible from the more frequent screen-level observations before the availability of the first superficial soil moisture observation. This feature allows a convergence in about 9 days.

These results, that have been obtained by considering rather accurate observations, show the capacity of the simplified 2D-VAR to assimilate observations available at different temporal intervals.

5. DISCUSSION

In the following years, the 2D-VAR using ISBA-A-gs will be implemented in a pre-operational version of the Météo-France hydrological modelling system SIM (Habets et al., 2007) over France. This work will be carried out in collaboration with other European national meteorological services and with ECMWF. This system will allow the near real-time monitoring of soil moisture, vegetation biomass, as well as carbon and water fluxes. The resulting soil moisture analysis will be used for the initialization of the future Météo-France high resolution atmospheric model AROME. The SMOSMANIA soil moisture network will permit to validate the SMOS Level 2/3 products and the operational ASCAT soil moisture products of EUMETSAT.

Currently, the assimilation scheme is being tested as for the optimal assimilation window length. At present, the availability of the different data sets varies significantly. While the data from the surface observational network are available at 6-hour intervals, soil moisture information from remote sensing platforms will be available approximately every 2 to 3 days, and LAI observations only every 10 days. This discrepancy will be a challenge, when all data are jointly assimilated.

6. ACKNOWLEDGMENTS

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