# Advances in land data assimilation at Météo-France

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## ABSTRACT

This paper reviews developments on land data assimilation undertaken at Météo-France through a number of collaborations (ALADIN and HIRLAM consortia, University of Melbourne, NILU research institute). The main focus is on an Extended Kalman Filter (EKF) developed in a land surface externalized platform SURFEX to allow the assimilation of screen-level observations, satellite derived soil moisture and leaf area index. The EKF should replace in the near future the current operational soil analysis based on an Optimum Interpolation scheme using only screen-level observations. Various results are summarized and areas of future research described.

## 1 Introduction

Land data assimilation is a generic term that refers to the analysis of land surface parameters (e.g. soil moisture, soil temperature, snow depth, albedo, leaf area index) by combining a-priori information (e.g. short range forecast, climatology) with available observations (e.g. satellite derived products, near-surface analysis) around an analysis time. Such surface analysis is provided by a so-called *Land Data Assimilation System (LDAS)*. For numerical weather prediction (NWP) applications, the objective is to improve the specification of these parameters as boundary or initial conditions to run short or medium range forecasts.

This paper provides a summary of developments undertaken at Météo-France in this area. First the main features of the operational deterministic NWP models are given. Then the first soil analysis scheme that was put in operations 25 years ago is presented. After a description of the current operational soil analysis scheme, various developments undertaken in order to improve this LDAS are summarized together with a number of open issues.

## 2 Main features of the NWP models at Météo-France

Météo-France runs operationnally three deterministic NWP models each one having its own atmospheric data assimilation system, with the following specifications (November 2009):

- *ARPEGE* is a spectral global stretched model (T538C2.4L60 - 15 km resolution over France) with a multi-incremental 6-h window 4D-Var assimilation system at (T107/T224) (90 km) [forecast range : 102 h]
- *ALADIN* is a spectral limited area model (E149x149C1L60 - 9.5 km resolution) with a 6-h window 3D-Var assimilation system [forecast range : 54 h]
- *AROME* is a spectral limited area model (E255x299C1L41 - 2.5 km resolution) with a 3-h window 3D-Var assimilation system [forecast range : 30 h]

The physical parameterizations include a TKE vertical diffusion scheme, a cloud microphysical scheme (4/5 hydrometeors), a shallow convection mass-flux scheme, the ECMWF radiation scheme, and a two-layer land surface scheme ISBA (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996). The *ARPEGE* and *ALADIN* models have also a representation of deep moist convection whereas the land surface scheme ISBA is run in a three-layer version (Boone et al., 1999) within the externalized surface modelling platform SURFEX (Le Moigne et al., 2009) in the *AROME* model.

## 3 Short history and current status on land data assimilation at Météo-France

### 3.1 Land data assimilation 25 years ago

The current land surface ISBA scheme (ISBA-2L) is derived from the force-restore method (Bhumralkar, 1975; Deardorff, 1977) that were used in the previous hemispheric spectral model *EMERAUDE* put in operations in 1985. The force-restore equations for surface temperature $T_s$, deep soil temperature $T_2$, superficial soil moisture content $w_g$ and deep soil moisture content $w_2$ write :

$$\begin{aligned}
\frac{\partial T_s}{\partial t} &= C_T(R_n - H - LE) + \frac{2\pi}{\tau_1}(T_2 - T_s) \\
\frac{\partial T_2}{\partial t} &= \frac{2\pi}{\tau_2}(T_s - T_2) \\
\frac{\partial w_g}{\partial t} &= \frac{C_1}{\rho_w d_1}(P_g - E_g) - \frac{C_2}{\tau_1}(w_g - w_2) \\
\frac{\partial w_2}{\partial t} &= \frac{C_2}{\tau_2}(w_g - w_2)
\end{aligned}$$

with $w_{sat} \times d_1$=10 mm, $\tau_1$=1 day and $\tau_2$=5 days. $P_g$ is the precipitation flux reaching the ground and $E_g$ is the surface evaporation. The main differences between this old surface scheme and ISBA are the use of constant values of the coefficients $C_T$=1.1$\times 10^{-5}$ J$^{-1}$m$^2$K, $C_1$=1, and $C_2$=1 (they depend upon soil moisture and soil texture in ISBA) and the absence of plant transpiration in the surface evaporation components (bare soil contribution only). Moreover, the deep water reservoir is described in ISBA with a physical depth $d_2$ instead of a corresponding time constant $\tau_2$ (here $\tau_1/\tau_2 = d_1/d_2$).

For these prognostic variables, soil analysis equations based on increments from a screen-level analysis of temperature $T_{2m}$ and relative humidity $RH_{2m}$ using SYNOP data have been proposed by Coiffier et al. (1987) :

$$\begin{aligned}
T_s^a &= T_s^b + (T_{2m}^a - T_{2m}^b) \\
T_2^a &= T_2^b + \left[\frac{\tau_1}{\tau_2}(T_{2m}^a - T_{2m}^b)\right] \\
w_g^a &= w_g^b + w_{sat}(RH_{2m}^a - RH_{2m}^b) \\
w_2^a &= w_2^b + w_{sat}\left[\frac{\tau_1}{\tau_2}(RH_{2m}^a - RH_{2m}^b)\right]
\end{aligned}$$

The superscript $a$ and $b$ correspond to the analysis and to the background (short-range forecast) respectively. For each variable, the final analysis $x^{a*}$ is weighted between the actual analysis $x^a$ and a climatological value $x^c$ :

$$x^{a*} = (1-\lambda)x^a + \lambda x^c$$

where $\lambda = 0.020$ for a 6-h assimilation cycle (time constant of 12.5 days).

The soil analysis equations reveal that corrections are more important for the surface variables than for the deeper ones and are applied at every analysis. It means that, in terms of causality, the origin of screen-level forecast errors is not identified : the soil analysis simply transfers atmospheric corrections into the soil with larger corrections for the superficial layer (closer to the atmosphere) and with a damping for the deep layer (similar to the energy and water forcings). In terms of turbulent fluxes, the soil corrections almost preserve sensible and latent heat components after the analysis (conservation of vertical gradients).

## 3.2 Current land data assimilation

The same methodology (use of screen-level analysis increments) has been adapted to the ISBA-2L scheme by Mahfouf (1991) with an emphasis on soil moisture ($w_g$, $w_2$) :

$$
\begin{aligned}
T_s^a &= T_s^b + \mu_1 (T_{2m}^a - T_{2m}^b) + \mu_2 (RH_{2m}^a - RH_{2m}^b) \\
T_2^a &= T_2^b + \nu_1 (T_{2m}^a - T_{2m}^b) + \nu_2 (RH_{2m}^a - RH_{2m}^b) \\
w_g^a &= w_g^b + \alpha_1 (T_{2m}^a - T_{2m}^b) + \alpha_2 (RH_{2m}^a - RH_{2m}^b) \\
w_2^a &= w_2^b + \beta_1 (T_{2m}^a - T_{2m}^b) + \beta_2 (RH_{2m}^a - RH_{2m}^b)
\end{aligned}
$$

A first obvious difference is to use both screen-level temperature and relative humidity to correct each soil variable (screen-level errors have to support each other to make significant corrections in the soil). Another difference (more fundamental) refers to the causality mentioned above. Mahfouf (1991) assumes that short range forecast errors at screen-level originate from errors in soil variables. Therefore, in order to estimate the coefficients $\alpha_i$ and $\beta_i$, single column model runs with perturbed initial soil moisture contents were performed and the response in terms of screen-level errors examined. Statistics providing correlations between screen-level and soil errors were computed in order to derive optimum interpolation (OI) coefficients (leading to an analysis with a minimum variance estimate).

This important difference had a number of consequences. Since the ISBA scheme accounts for vegetation transpiration taking place in the root zone, deep soil moisture corrections are larger for $w_2$ than for $w_g$ (variable for which errors will persist over longer time scales). Screen-level errors can only reflect soil moisture errors when the turbulent fluxes are large in order to provide a physical link between the soil and the boundary layer (i.e. daytime with significant radiative forcing).

Statistics were derived by Mahfouf (1991) in clear-sky summer conditions. The OI coefficients are then strongly reduced (empirically) in meteorological situations where near-surface forecast errors are likely not to be induced by the surface. An analytical formulation for $\alpha_i$ and $\beta_i$ coefficients (dependencies with solar time, soil texture and vegetation properties) has been proposed by Bouttier et al. (1993) and revised by Giard and Bazile (2000).

For soil temperatures, the coefficients proposed by Coiffier et al. (1987) were kept ($\mu_1 = 1$, $\mu_2 = 0$, $\nu_1 = \tau_1/\tau_2$, $\nu_2 = 0$) even though in a recent study (Mahfouf et al., 2009) it has been shown that these coefficients exhibit a strong diurnal cycle (with low values during daytime) and that they are larger for $T_2$ than for $T_s$ (see next section).

The OI soil analysis was implemented operationnally in the *ARPEGE* model with the ISBA scheme in March 1998 (Giard and Bazile, 2000). This soil analysis uses a climatological relaxation constant of $\lambda = 0.045$ (time constant of 5.5 days) towards the GSWP climatology (at one degree resolution). The OI coefficients are also strongly reduced in case strong wind, precipitation, frozen soil and snow on the ground. The soil moisture analysis is modified in order to keep $w_2$ between $veg \times w_{wilt}$ and $w_{fc}$, and $w_g$ between 0 and $w_{fc}$ (where $veg$ is the vegetation fraction, $w_{wilt}$ and $w_{fc}$ the water contents at wilting point and field capacity respectively). The reason is that the link between soil moisture content and screen-level parameters takes place through the evapotranspiration flux that only depends upon soil moisture between $w_{fc}$ and $w_{wilt}$. The use of a linear regression through an OI scheme does not allow to account for this non-linear behaviour (lack of sensitivity below $w_{wilt}$ and above $w_{fc}$). A temporal smoothing of the deep soil moisture increments (over the last four analyses) is performed, and the bias on $T_{2m}$ analysis increments is removed (Giard and Bazile, 2000).

A problem associated with the Monte-Carlo experiments performed by Mahfouf (1991) was that the standard deviation of background errors for the deep soil moisture content was set to a rather large value of 0.05 $m^3/m^3$ (with respect to a typical value from a short-range forecast). The advantage of such prescription is to span to whole range of soil moisture values from very dry to very moist soils and to produce background error statistics with contrasted soil conditions. This technique provided realistic error correlations with a small number of Monte-Carlo experiments but the soil moisture error variances needed to be rescaled. This was pointed out by Douville et al. (2000) who specified a standard deviation for $w_2$ of 0.01 $m^3/m^3$ in the ECMWF OI based on lagged forecasts of the surface water budget (precipitation minus evaporation minus runoff) with the 3D ECMWF model.

At Météo-France, the OI coefficients for $w_2$ were reduced by a factor of 3 in October 1999 and a cloudiness dependency was also included. In May 2003, the OI coeeficients were reduced again by a factor of 2, the background error statistics for the screen-level analysis were improved, and a dependency with the solar zenith angle was introduced as in Douville et al. (2000). Moreover, the temporal smoothing on $w_2$ increments and the bias correction on $T_{2m}$ increments has been removed. Finally, a spatial smoothing (Laplacian filter) was introduced on the soil wetness index to remove small scale noise present in the soil moisture analyses.

In February 2009, this version of the soil analysis (without climatological relaxation) was introduced for the *ALADIN* model (before that date *ALADIN* was starting from an interpolation of the *ARPEGE* soil analysis). The *AROME* model, operational since December 2008, does not have yet a soil analysis (for a number of technical and scientific issues), and therefore, each forecast starts from a soil analysis produced for the *ALADIN* model.

This soil analysis developed at Météo-France and based on OI with screen-level parameters is currently used by a number of NWP centers : in the ALADIN consortium (Giard and Bazile, 2000), in the HIRLAM consortium (Rodriguez et al., 2003), at ECMWF (Douville et al., 2000; Drusch and Viterbo, 2007), at Environment Canada (Bélair et al., 2003). The German Weather Service and the UK MetOffice also use screen-level observations to correct soil moisture contents but with a simplified Extended Kalman Filter (Hess, 2001) and with a physically derived analytical formulation (Best and Maisey, 2002) respectively.

Many weather centers are now developing new LDASs in order to overcome the weaknesses of simpler schemes, that is their lack of flexibility for accounting new (and combined) observation types and new surface analysis variables. Indeed, a number of satellite missions have (or will have) onboard microwave instruments sensitive to the superficial soil moisture (e.g. AMSR-E/Aqua (2002), ASCAT/MetOp (2006), SMOS/ESA (2009), SMAP/NASA (2014)). Over specific domains precipitation analyses and satellite derived downward radiative fluxes (e.g. EUMETSAT LandSAF) are available and should be included in LDASs. Finally, since the development of the two-layer version of ISBA, new versions are available (multi-layer soil scheme, dynamical vegetation scheme) with additional prognostic variables that would be difficult to include in the current OI scheme.

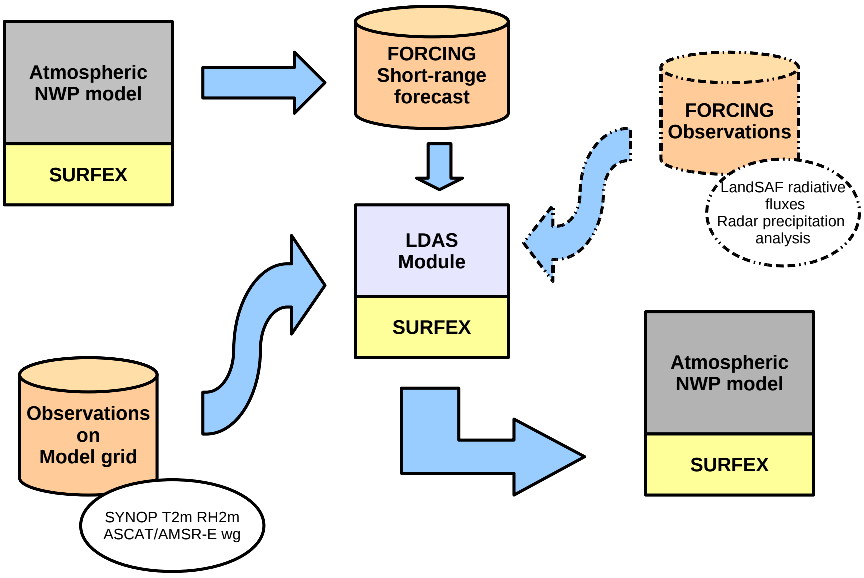

*Figure 1: Coupling between an atmospheric NWP model and an externalised Land Data Assimilation System using the externalized surface modelling platform SURFEX*

# 4 Development of an offline land data assimilation system

## 4.1 Main features

The surface models (ISBAs/Towns/Lakes/Oceans) have been externalized at Météo-France from the atmospheric models into a platform called SURFEX (SURFace EXternalized) (Le Moigne, 2009). SURFEX can be coupled to any atmospheric model used at Météo-France (*ARPEGE*, *ALADIN*, *AROME*, *Méso-NH*) using the internal coupling strategy of Best et al. (2004). SURFEX can also be used in offline mode (e.g. validation studies against field experiments). A number of new surface analysis schemes (described herafter) are being developed within SURFEX (offline version / semi-coupled) following a strategy schematically described in the flowshart of Figure 1. The atmospheric model (run with SURFEX) provides the atmospheric forcing necessary to run the surface in offline mode over a given assimilation window. Observations interpolated onto the model grid are used in the LDAS system that provides an analysis (soil/vegetation state) to be used as initial conditions to launch the atmospheric model forecast over the next assimilation window. The soil analysis can be done before the upper air analysis to improve the assimilation of near surface observations in the atmosphere. Currently three main surface analysis schemes are available in SURFEX :

- An *Optimum Interpolation* (to reproduce the current operational scheme within SURFEX)
- An *Extended Kalman Filter* (with a simplified version where the background errors are not evolved)
- An *Ensemble Kalman Filter* (with two flavours developed by a Norvegian research institute NILU in collaboration with the HIRLAM consortium)

### 4.2 Comparaison of the OI and EKF soil analysis schemes in ALADIN-France

In a first stage, the EKF (simplified) version has been compared to the OI scheme for the assimilation of screen-level observations in the *ALADIN-France* model (Mahfouf et al., 2009). The EKF provides the dynamical OI coefficients ($\alpha_i$, $\beta_i$, $\mu_i$ and $\nu_i$) as the elements of the Kalman gain matrix given by :

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

where the background and observation error covariance matrices **B** and **R** are prescribed and the Jacobian of the observation operator **H** is obtained in finite differences (example given for $w_2$) :

$$\mathbf{H} \approx \frac{\mathbf{y}^t(w_2^0 + \Delta w_2^0) - \mathbf{y}^t(w_2^0)}{\Delta w_2^0}$$

where $\mathbf{y}^t$ is the simulated observation at time $t$ ($T_{2m}$, $RH_{2m}$) and $\Delta w_2^0$ is a small initial perturbation. This technique is affordable because the ISBA scheme is run in offline mode and soil columns are treated independently.

Figure 2 compares the OI and EKF coefficients $\beta_1$ and $\beta_2$ for 1 July 2006 at 1200 UTC over the *ALADIN-France* domain. It appears that these coefficients are consistent and have the same order of magnitude. However, larger values by a factor of 2 can be noticed for $\beta_2$ with the OI. Regions with precipitation (Central Europe) are associated with small values of the coefficients (weak coupling between the surface and the boundary layer). Other regions having very small values of $\beta_1$ and $\beta_2$ with the EKF are associated with very dry soils below the wilting point (central Spain, Ebro valley, Vendée region). When $w_2$ is below $w_{wilt}$, plant transpiration becomes negligible and the surface evaporation does not depend upon soil moisture. Such non-linear effect cannot be described by the OI coefficients since they do not depend upon the actual soil moisture conditions. Over Poland, the EKF coefficients are larger than with the OI formulation because the soil moisture in the root zone is slightly above the wilting point value (strong non-linear dependency with the canopy resistance around this threshold).

The other OI and EKF coefficients are compared as mean and standard deviations in Figure 3 for 1 July 2006. The time window is 06-12 UTC for $\alpha_i$, 00-06 UTC for $\mu_i$ and 18-24 UTC for $\nu_i$ corresponding to their maximum values. It appears that the $\alpha_i$ coefficients are strongly overestimated by the OI with respect to the EKF. This corresponds to the overestimation of the variance of background errors of $w_2$ that was noticed for the $\beta_i$ and corrected by a factor of 6 reduction with respect to the initial formulation. The use of a larger coefficient for $T_s$ than for $T_2$ in the OI is not supported by the EKF. The use of $RH_{2m}$ as a predictor brings information since there is a strong negative correlation with $T_{2m}$ (non zero values of $\mu_2$ and $\nu_2$). Finally, the coefficients $\mu_i$ and $\nu_i$ have a strong diurnal cycle with larger values during nighttime. Since the surface energy and water budgets are less sensitive to the specification of $w_g$, $T_s$ and $T_2$, than to the root-zone soil moisture $w_2$, this explains why such inconsistencies remain in the operational system at Météo-France.

### 4.3 Preliminary studies on the assimilation of $w_g$ satellite products

The SURFEX EKF has been used to assimilate superficial soil moisture derived from AMSR-E/Aqua (Draper et al., 2009), SCAT/ERS and ASCAT/MetOp (Mahfouf, 2010). The model Jacobians (i.e. link between $w_g$ and $w_2$) have been studied and found rather linear. The ISBA 2L version provides a strong link between the surface layer and the root zone : this link is likely too strong from the vertical discretization and also from the use of a single energy balance (one temperature for bare soil and vegetation canopy). However, it is simple enough for an analytical formulation to be derived (Mahfouf, 2010). The importance of a bias correction scheme has been emphasized (Draper et al., 2009) together with data quality controls. Draper et al. (2010) have pointed out that the specification of the covariance

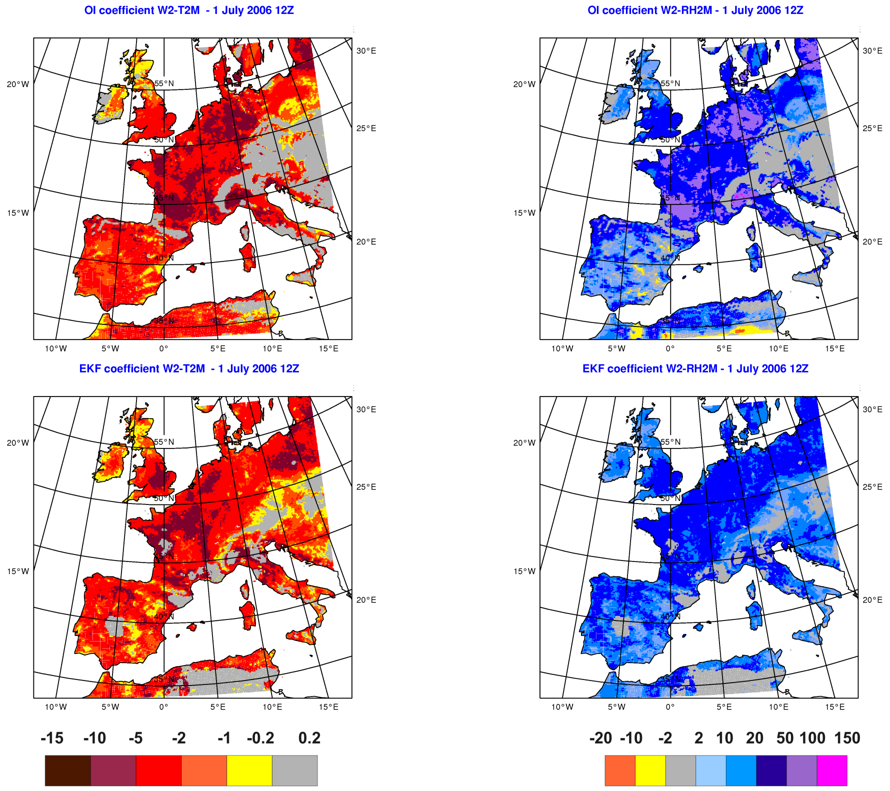

*Figure 2: OI vs EKF coefficients : $\beta_1$ (mm/K) and $\beta_2$ (mm) (01/07/2006 at 12 UTC) [coefficients are multiplied by the soil depth $d_2$ in mm]*

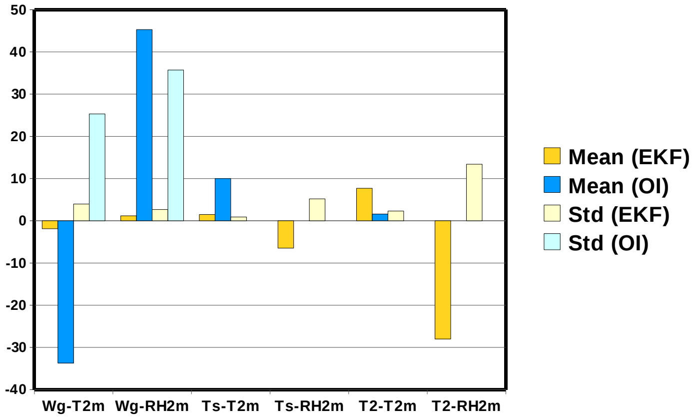

*Figure 3: Statistics of OI vs EKF coefficients : $\alpha_i$, $\mu_i$ and $\nu_i$ (mean and standard deviation values) for 1 July 2006*

matrix of background errors **B** is an issue with ISBA-2L for combined assimilation of conventional and satellite observations. Indeed, the background error for $w_2$ is about 0.01 $m^3/m^3$ (as discussed above) whereas the observation error for $w_g$ ranges between 0.04 $m^3/m^3$ (SMOS expected accuracy) and 0.06 $m^3/m^3$ (SCAT and ASCAT estimated accuracy), and the observation operator **H** is at most equal to one. Therefore :

$$\mathbf{HBH}^T \ll \mathbf{R}$$

leading to not enough weight of the satellite derived product $w_g$ in the LDAS.

### 4.4 Preliminary studies on the assimilation of satellite derived surface albedo and *LAI*

The assimilation of satellite products on surface albedo and leaf area index (*LAI*) has recently started at Météo-France (2008) in order to improve current climatological specifications. The near real time availability of a number of products (MODIS *LAI*, LandSAF albedo) should allow a better characterization of surface properties that are important for the energy and carbon surface budgets. Since these properties evolve rather slowly compared to atmospheric quantities, there availability can be less frequent (e.g. every week) than what is needed for the water budget (every two or three days). Another consequence is that the associated forward operator is close to identity (assimilation of satellite reflectances has not been tried yet). A feasibility study has been undertaken where the daily LandSAF surface albedo is combined optimally to a climatological albedo with a Kalman filter. The total albedo is split into bare soil and vegetation contributions using the vegetation fraction *veg* from climatology ; the analysis error is propagated in time to account for cloudy periods without observed values. Positive impacts have been noticed on $T_{2m}$ forecast scores in the *ALADIN* model. Using a version of the ISBA scheme describing photosynthesis and plant dynamics, the *LAI* has been assimilated together with superficial soil moisture content in an Extended Kalman Filter allowing a consistent constraint from the observations on the energy, water and carbon budgets. The major difficulty concerns the specification of observations and background errors. Feasibility studies at local scale (Muñoz-Sabater et al., 2008) will be extended over the whole domain of France within the EC FP7 project GEOLAND2.

## 5 Current activities and remaining issues

Hereafter are summarized the ongoing activities related to land data assimilation at Météo-France in collaboration within ALADIN and HIRLAM consortia (and also within EUMETNET SRNWP).

An important activity in 2010 will concern the development of a dedicated soil analysis for the mesoscale high resolution model *AROME*. Since we would like to have an operational system as soon as possible, it is planned to adapt the OI scheme to the three layer version of ISBA and to extend the initialisation of soil temperatures to the urban model TEB (Masson, 2000).

Improved precipitation forcing (analyses from radar and/or raingauges) will be used within the EKF to correct soil moisture contents by combining optimally this information with the precipitation forcing produced by a model short-range forecast (instead of a direct insertion as in the NOAA/NASA NLDAS). The technique will use sensitivity of soil moisture with respect to precipitation. A preliminary study has been done over the Czech Republic with high resolution radar products and the *ALADIN* model in July 2008.

Studies on the assimilation of ASCAT soil moisture will be continued within the *ALADIN* 3D-Var both at Météo-France and at ZAMG (Austrian Weather Service) and also within the hydrometeorological system SIM (Habets et al., 2008) over France. The impact of this operational product will be assessed for both weather and hydrological forecasts. Focus will be on improving bias correction schemes and data quality controls.

Another area of improvement of the EKF will concern the specification and/or estimation of model and background error statistics. It is planned to use forecast or assimilation ensembles to derive more realistic statistics, and also to perform a-posteriori diagnostics (Desroziers et al., 2005) to evaluate them. Since an ensemble Kalman filter version is available within SURFEX comparisons with the statistics derived from this system and from the EKF will be done in collaboration with NILU.

Efforts will also be devoted in improving the spatialization tools needed for snow depth and screen-level variable analyses. In particular we want to include anisotropy effects (produced by orography and sea/land contrasts) in the CANARI OI. Regarding snow depth analysis, snow cover extent will be included using geostationnary satellite imagery along the lines used at ECMWF (Drusch et al., 2004). Part of these developments will be undertaken within the three-year EC FP7 project EURO4M (in collaboration with SMHI on this particular item).

The interest of land surface albedo analysis will be further evaluated for NWP applications and put in operations rapidly. Examination of winter situations will also require some attention since during freeze/thaw events aliasing between soil temperature and water content corrections can arise.

Since SMOS has been successfully launched in November 2009, superficial soil moisture derived from the L-band radiometer will be compared to model counterparts and a similar methodology for data assimilation to that already developed for ASCAT will be followed.

Finally, it is important to recall that land data assimilation heavily relies on the quality of the forward soil/vegetation scheme. The ISBA scheme will be improved on several aspects (soil depth/root-zone specification, surface energy balance, vertical soil discretization, soil textural properties) that should be beneficial to land data assimilation.

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