Advances in land data assimilation at ECMWF

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ABSTRACT

This paper presents the European Centre for Medium-Range Weather Forecasts (ECMWF) land surface analysis system and its recent developments. A new soil moisture analysis scheme based on a point-wise Extended-Kalman Filter (EKF) for the global land surface has been developed. As the previous Optimal Interpolation (OI) scheme, it use proxy observations (2 m air temperature and relative humidity) to analyse soil moisture. As part of the EKF implementation strategy a new surface analysis structure has been developed in 2009 to separate completely the upper air analysis and the surface analysis. These technical developments are shortly described in this paper. An evaluation of the EKF performances is conducted through a set of three 1-year analysis experiments. The impact of the EKF compared to the OI, on soil moisture, 2m temperature and relative humidity is investigated. The use of satellite data from the active sensor ASCAT is also briefly presented to investigate the possibility of combining conventional observations and satellite data for the soil moisture analysis.

1 Introduction

A number of current operational soil moisture analysis systems in Numerical Weather Prediction (NWP) are based on analysed or observed screen-level variables, (2 m temperature and relative humidity). For instance, at Météo France (Giard and Bazile, 2000), ECMWF (Mahfouf et al., 2000) and at Environment Canada (Bélair et al., 2003) Optimal Interpolation (OI) algorithm is used operationally. The OI scheme presents several weaknesses, including the fact that it is not flexible enough to cope with the current increase in model complexity and data availability. Land surface processes and their initialisation are of crucial importance to address the challenge of seamless (from weather to seasonal) NWP. In particular it is expected to be of high interest to assimilate new satellite based soil moisture observations from the METOP/ASCAT (Advanced SCATterometer, Scipal et al., 2008). The use of SMOS (Soil Moisture and Ocean Salinity) is also expected to be of high interest for NWP and SMOS data monitoring is currently under implementation at ECMWF as described by (Muñoz Sabater et al., 2010; de Rosnay et al., 2009). The German Weather Service (Deutsche Wetter Dienst) was the first NWP centre to use a 'simplified' Extended Kalman Filter (SEKF) for NWP (Hess, 2001). Météo-France developed an offline SEKF soil analysis scheme within the SURFace EXternalized system used for research applications (Mahfouf et al., 2008). ECMWF also recently developed an SEKF system for the soil moisture analysis. First investigations were conducted at locale scale by Seuffert et al. (2003), and at global scale by Drusch et al. (2009) who describe the SEKF surface analysis and show preliminary one-day results at global scale.

This paper presents the ECMWF SEKF soil moisture analysis implementation in operations in the Integrated Forecasting System (IFS) cycle 36r3. It investigates the impact of the SEKF on the forecast scores of atmospheric and soil moisture variables. Next section briefly describes the OI soil-moisture analysis scheme, used in operations until IFS cycle 36r2, and the new SEKF surface analysis scheme used from IFS cycle 36r3 in 2010. The SEKF operational implementation strategy, including a new structure of the surface analysis within the IFS, is discussed. Section 3 presents results from a set of 1-year analysis experiments. Comparison between the OI and the SEKF soil moisture analysis with and without ASCAT data assimilation is presented. Section 4 concludes.

2 The ECMWF land surface analysis system

At the date of the workshop in November 2009, the version of the ECMWF's IFS is the cycle 35r3 which was implemented in operations on 8 September 2009. Within the IFS, the surface analysis provides initial conditions at the forecast model's lower boundary. The surface analysis is independent from the 4D-VAR (Four Dimensional VARiational data assimilation) atmospheric analysis, so the feedback between the forecast model and the surface analysis relies on the fact that the model-predicted screen level fields provide the first guess departures for the land surface analysis, which in turn provides the initial conditions to the forecast model.
The surface analysis is performed at fixed times at 00, 06, 12, and 18 UTC when the synoptic observations are obtained. It is scheduled to run immediately after the two main 12-hour window 4D-VAR atmospheric analyses that cover the periods from 21 to 09 UTC and 09 to 21 UTC.

Surface analysis tasks include ocean surface analysis and land surface analysis. Over ocean surfaces, the analysis consists in interpolating the UK Met Office (UKMO) Operational Sea Surface Temperature and sea Ice Analysis (OSTIA) products to the ECMWF model grid. For great lakes area this product is combined with the product of the National Center for Environmental Prediction (NCEP). The land surface analysis at ECMWF includes snow depth analysis, screen level parameters analysis (2 m temperature T_{2m} and relative humidity RH_{2m}), soil moisture and soil temperature analysis. Snow depth analysis is based on a Cressman analysis using SYNOP snow depth data and NOAA/NESDIS snow cover information to constrain the assimilation system, as described in Drusch et al. (2004). The screen level parameters analysis relies on an OI scheme using SYNOP data. It provides a two-dimensional statistical interpolation from which the analysis increments are computed at each model grid point (Mahfouf et al., 2000). The screen level parameters analysis is then used as input of the soil moisture and temperature analysis as described in the next subsections.

2.1 The current operational OI scheme for soil moisture and temperature analysis

The OI soil moisture analysis is based on the relationship between soil variables (moisture and temperature) and near-surface atmosphere established by evaporation processes. Soil wetness deficit is assumed to be associated to a lack of air humidity and temperature overestimation at the screen level. On the contrary, soil water excess is assumed to be related to air humidity overestimation and air temperature underestimation.
The OI soil moisture analysis is described in details Mahfouf et al. (2000). It is constrained by "observations" (screen level parameters analysis) which are relatively weakly related to soil moisture. So, soil moisture is a sink variable, in which errors introduced through the atmospheric forcing and the land surface model, HTESSEL, (Tiled ECMWF Scheme for Surface Exchanges over Land, Balsamo et al., 2009) accumulate. As shown by Drusch and Viterbo (2007) the OI soil moisture analysis procedure corrects the evaporation and heat fluxes at the surface, without producing improved soil moisture fields.

The OI soil moisture analysis has been used in operations at ECMWF from 1999 (cycle 21r2). It will be replaced in 2010 by the SEKF soil moisture analysis in cycle 36r3.

2.2 The ECMWF SEKF soil moisture analysis

In order to optimally combine conventional observations with satellite measurements, an advanced surface data assimilation system has been recently developed at ECMWF (Drusch et al., 2009; Seuffert et al., 2003). The core of the SEKF system relies on the solution for the analysed state $\mathbf{x}_a$ at time t and expressed as:

$$\mathbf{x_a}^t = \mathbf{x_b}^t + \mathbf{K}\left(\mathbf{y}^t - \mathbf{H}\mathbf{x}_\mathbf{b}^\mathbf{t}\right) \quad (1)$$

with $\mathbf{x}_b$ the background state vector, **H** the Jacobian of the observation operator and **K** the gain matrix. In this system the state vector is soil moisture and the observation vector **y** can be conventional observations such as 2 m temperature and relative humidity, as used in the OI. The elements of the Jacobian matrix are estimated in finite differences by perturbing individually each component x_j of the control vector **x** by a small amount δx_j. To this end a control 12 hour unperturbed forecast and one perturbed forecast is performed per analysed variable (for the soil analysis 3 soil layers are analysed).

2.3 SEKF implementation

Although the OI system is limited in terms of both performances and flexibility to use different types of data, the OI system presents the great advantage of being very cheap in computing time. At any resolutions the OI time consumption remains negligible, ranging from about 3 seconds in CPU at T159 (125km), 20 seconds in CPU at T799 (23km). The SEKF surface analysis is far more expansive than the OI system. At T159 its time consumption is close to 3000 seconds in CPU and it is close to 2. 10^5 seconds at T799, for which is represents about one fifth of the 4D-VAR time consumption.

As part of the SEKF implementation, a new structure of the surface analysis was developed and implemented in IFS cycle 35r3, as described in (Vasiljevic et al., 2009). In the new structure, the surface analysis is independent of the upper air analysis. The observational dependency was resolved by creating a new surface analysis dedicated ODB. The field dependency issue mentioned above is resolved in the new surface analysis structure by using the first guess fields instead of the upper air analysis output fields.

The new surface analysis and the upper air analysis are separated so they can be run in parallel. The surface analysis in not any more in the critical path, opening thereby the possibility to increase the surface analysis elapse time significantly. This new surface analysis constitutes an essential step in the ongoing developments of the surface analysis in the IFS. By removing the surface analysis tasks from the time critical path, it enables to implement the Extended Kalman Filter soil moisture analysis.

In addition to the re-organisation of the surface analysis an approach has been developed to compute offline the SEKF Jacobians within the physics of the IFS, reducing thereby the cost of the SEKF by a factor of three. This approach will be used from IFS cycle 36r4.

2.4 Numerical experiments

Replacing the OI by an SEKF approach is a major change in the surface analysis. Therefore, long term evaluation, for a full annual cycle is necessary to investigate the reliability of the use of the SEKF for the soil moisture analysis and the impact on the forecast low level atmospheric parameters such as 2m temperature and relative humidity. Three experiments have been conducted for 01 December 2008 to 30 November 2009 (Table 1). The 'OI' experiment uses the OI surface analysis, using the screen level parameters SYNOP observations. The 'SEKF' experiments uses the SEKF soil moisture analysis with also the SYNOP observations of the screen level parameters. These two experiments only differ in the method used for the soil moisture analysis. Observations used for the analysis are exactly identical. The 'SEKF+ASCAT' experiment has been conducted for the same one year period, using the SEKF in which screen level parameters SYNOP data is used together with the ASCAT soil moisture data. In this

Experiment	Period	Resolution	Cycle	Description
f8ua	2008120100-2009113012	T255 (80km)	36R1	default (OI)
f9hl	2008120100-2009113012	T255 (80km)	36R1	SEKF
f9hm	2008120100-2009113012	T255 (80km)	36R1	SEKF+ASCAT

Table 1: Numerical experiments conducted to compare the OI and the SEKF soil moisture analysis.

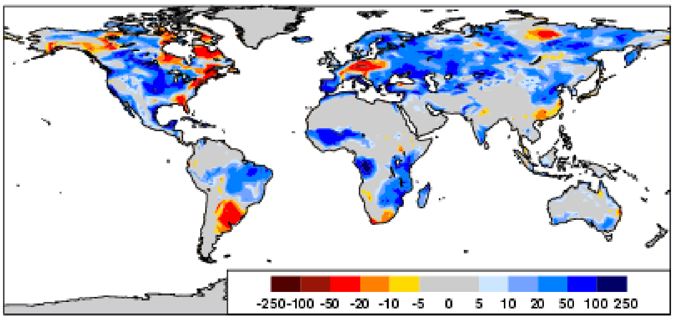
last experiment, ASCAT soil moisture data is matched to the ECMWF IFS model soil moisture using a Cumulative Distribution Function matching as described in Scipal et al. (2008).

3 Results

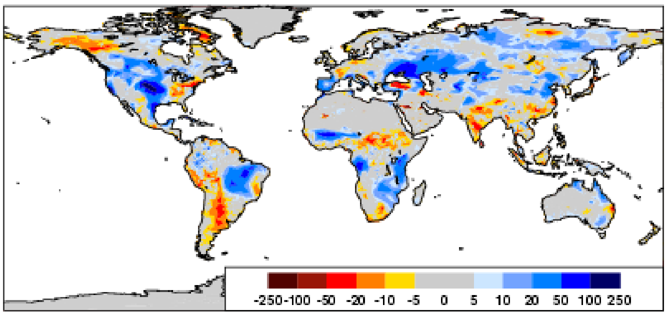
Figure 1 shows cumulated soil moisture analysis increments for July 2009 (in mm) for the OI experiment in (a), for the SEKF experiment in (b) and the difference between absolute values of SEKF and OI in (c). It clearly indicates that analysis increments are much reduced when the SEKF soil moisture analysis is used instead of the OI. Analysis increments per soil depth (not shown) indicate that the reduction in analysis increments mainly occurs in the second and third soil layers. The OI increments are very high in the deep soil layers since they are computed in volumetric values for the surface soil layer and simply converted into water equivalent according to the different soil layer thicknesses. This leads to compute unrealistically large increments with the OI. The SEKF soil moisture increments result from the Jacobians computation, which is performed separately for each analysed soil layer and which accounts for the weaker relationship of the screen level parameters with deep soil moisture than with surface soil moisture.
Figures 2 shows screen level parameters analysis verification over Africa for the three experiments for one annual cycle from December 2008 to November 2009. Using the SEKF soil moisture analysis reduces the 2 meter temperature cold bias significantly all the year along. This is consistent with a reduction of the soil moisture increments and also leads to have lower specific humidity.
Figure 3 shows soil moisture verification over the SMOSMANIA network (Calvet et al., 2007) for January 2009 to August 2009 (availability of calibrated SMOSMANIA data). It shows much higher performances (particularly in terms of correlation) of the soil moisture analysis when the SEKF is used compared to the OI. Using the ASCAT data that the SEKF soil moisture has a mitigated effect depending on the stations and it need to be further investigated.

4 Conclusion

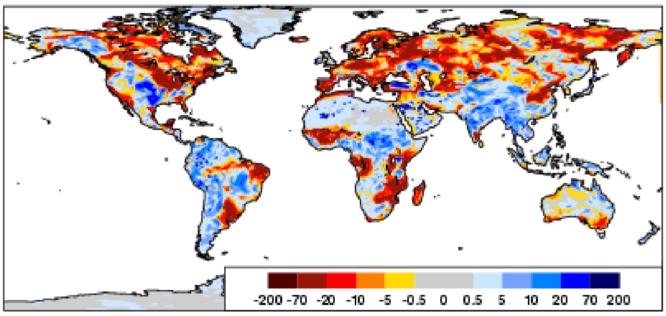
This paper presents the new SEKF soil moisture analysis implementation in IFS cycle 36r3. It shows results of the SEKF compared with the OI soil moisture analysis for a one year period from December 2008 to November 2009. The SEKF soil moisture analysis drastically reduces the soil moisture analysis increments compared to the OI. It generally improves the 2 meter temperature scores by reducing the night time cold bias. Specific humidity shows generally drier conditions with the SEKF than with the OI. Soil moisture evaluation against ground measurements from the SMOSMANIA network is also presented (layers 1 and 2). ECMWF soil moisture is in general good agreement with ground observations, with mean correlations values higher than 0.78 for the two layers. Using the SEKF instead of the OI improves significantly the soil moisture analysis, leading to a remarkable agreement between ECMWF soil moisture and ground truth (mean correlation higher than 0.84 for SEKF and SEKF+ASCAT). Using ASCAT soil moisture data does not impact on screen level variables and it has a slight impact on soil moisture analysis.



(a) OI (f8ua)

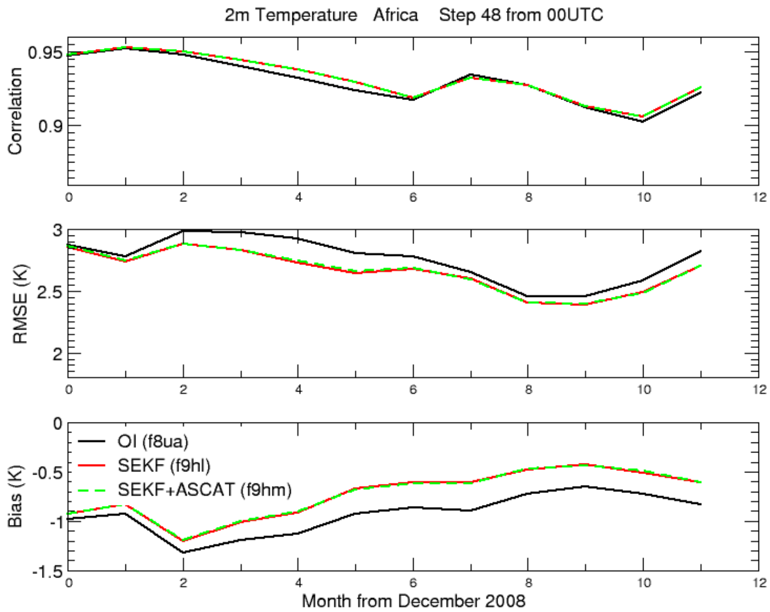


(b) SEKF (f9hl)

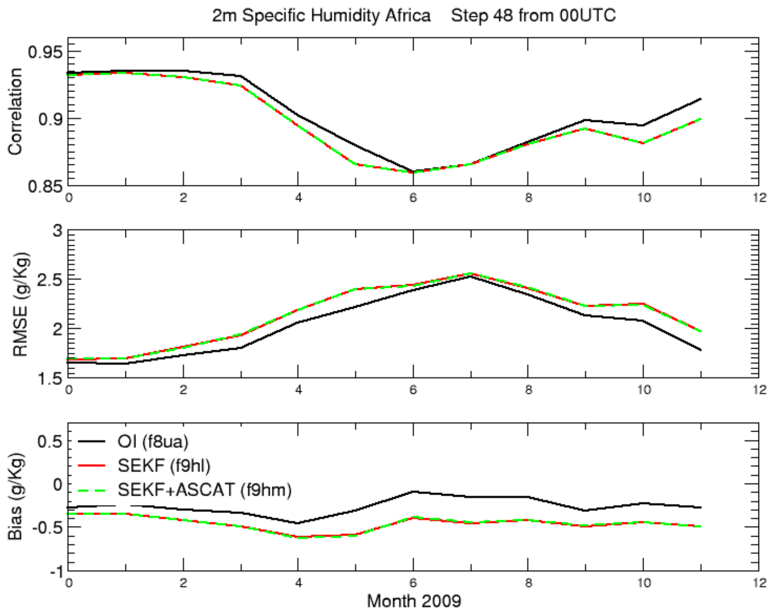


(c) |SEKF-OI| (|f9hl|-|f8ua|)

Figure 1: Soil moisture analysis increments, in mm, cumulated for July 2009 for the OI experiment (top), the SEKF experiments (middle) and difference of absolute values of soil moisture increments of the SEKF and the OI experiments.

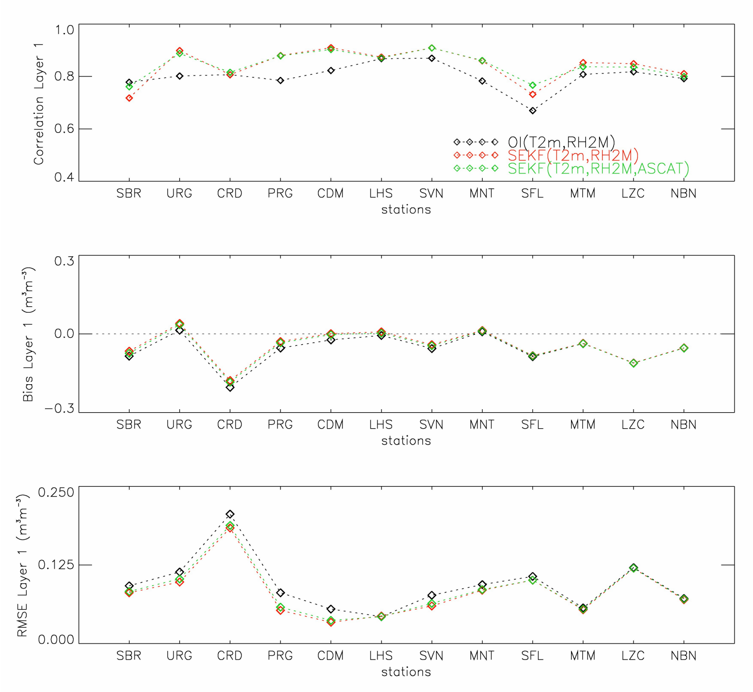


(a) Africa



(b) Africa

Figure 2: Temperature and specific humidity at 2m: verification against SYNOP over Africa (00UTC, step 48).



(a) First Layer (0-7cm)

Figure 3: Surface soil moisture verification of the analysis at 00UTC for the three experiments, against the 12 stations of the SMOSMANIA soil moisture Network in South of France.

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