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A simplified Extended Kalman Filter for the global operational soil moisture analysis at ECMWF

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Abstract

A new land surface analysis system based on a simplified point-wise Extended Kalman Filter (EKF) was implemented at ECMWF in the global operational Integrated Forecasting System (IFS) in November 2010. This system will allow consistent and optimal analyses of land surface parameters like soil moisture, soil temperatures, snow and vegetation properties. As part of the system implementation the surface analysis structure has been revised to permit an independent and parallel computation with the upper-air 4D-Var analysis. The new analysis system is used for the soil moisture analysis, replacing the previous Optimum Interpolation (OI) scheme. Similar to the OI system, the simplified EKF uses 2-metre air temperature and relative humidity observations from the SYNOP (land surface synoptic report) ground based networks to analyse soil moisture. This paper describes the new land surface analysis, its application for analysing soil moisture, and initial verification results that supported its operational implementation at ECMWF. The performance is evaluated based on a set of one-year analysis experiments. The simplified EKF is compared to the OI, on soil moisture, 2m temperature and relative humidity, showing a consistent improvement on screen level parameters and soil moisture forecasts. To demonstrate the potential of the new analysis scheme soil moisture derived from ASCAT (Advanced Scatterometer) has been assimilated through the simplified EKF.

1 Introduction

It is widely recognised that land surface processes determine the lower boundary conditions of the atmosphere and the partitioning of energy between sensible and latent heat fluxes (Entekhabi et al., 1999; Koster and Suarez , 1992; Sukla and Mintz , 1982). In climate models and in Numerical Weather Prediction (NWP) models, surface-atmosphere interaction processes are represented by Land Surface Models (LSMs). LSMs have been improved considerably in the last two decades. Nowadays LSMs represent exchanges of water and energy through the soil-plant-atmosphere continuum with a good consistency between land surface fluxes and soil moisture (Balsamo et al., 2009; de Rosnay et al., 2002). Some LSMs also represent river routing, as part of the continental branch of the hydrological cycle (Decharme and Douville , 2006) or account for interactions between hydrology, vegetation phenology and carbon cycle (Krinner et al., 2005).

Land surface initialisation is of crucial importance for NWP. Soil moisture in particular was shown by a number of studies to have a significant impact on weather forecast skill at short and medium range (van den Hurk et al., 2008; Drusch and Viterbo, 2007; Beljaars et al., 1996) as well as at seasonal range (Weisheimer et al., 2011; Koster et al. , 2011, 2004). As shown by Mahfouf (1991), near surface meteorological observations of 2-metre temperature and relative humidity, which are measured routinely by the SYNOP (land surface synoptic report) operational network, can be used to infer realistic soil moisture estimates. The first soil moisture analysis system used for operational NWP was implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) in 1994 to prevent the LSM from drifting to dry conditions in summer. It was based on a nudging approach that corrected soil moisture using lowest atmospheric level specific humidity analysis increments.

In 1999, an Optimum Interpolation (OI) soil moisture analysis was implemented operationally at ECMWF to replace the nudging scheme (Mahfouf et al., 2000). The OI soil moisture analysis relies on the fact that soil wetness and 2-metre temperature (relative humidity) errors are assumed to be negatively (positively) correlated. Therefore the 2-metre analysis increments of temperature and relative humidity are used as input for the OI soil moisture analysis (Mahfouf et al., 2000). The OI soil moisture analysis was used in operations at ECMWF from July 1999 to November 2010. It was used for the ECMWF re-analyses ERA-40 (Uppala et al., 2005) as well as in the current ERA-Interim (Dee et al., 2011). An OI soil moisture analysis is also used for operational NWP at Météo-France (Giard and Bazile, 2000) and at Environment Canada (Bélair et al., 2003), as well as in the High Resolution Limited Area Model

(HIRLAM, Rodriguez et al., 2003). Drusch and Viterbo (2007) showed that the OI soil moisture analysis scheme based on screen level parameter information improves the boundary layer forecasts skill, but not the soil moisture analysis in which errors are allowed to accumulate. In addition "the OI technique is not flexible enough to easily account for new observation types" (Mahfouf et al., 2009).

A number of studies were conducted in recent years to investigate the relevance of using variational and Kalman Filter approaches to analyse soil moisture. The German Weather Service (Deutscher Wetterdienst) implemented in 2000 a simplified Extended Kalman Filter (EKF) soil moisture analysis using screen level parameters information (Hess, 2001). They proposed an approach to explicitly compute Jacobians in finite differences based on perturbed simulations. Based on this approach Météo-France developed an offline simplified EKF to analyse soil moisture in the SURFace EXternalized system used for research applications (Mahfouf et al., 2009).
Mahfouf (2010) evaluated on a four-week period the impact of ASCAT (Advanced SCATterometer) soil moisture data assimilation in a simplified EKF in a research branch of the the limited area model, Aire Limitée Adaptation Dynamique developpement International (ALADIN/France) 3D-Var assimilation system. He showed a mitigated impact, positive on relative humidity and negative on 2-metre temperature. Further studies were conducted to investigate the use of satellite data to analysis soil moiture, using a range of approaches based on simplified EKF (Draper et al., 2011) or the equivalent simplified 2D-Var Balsamo et al. (2007), as well as EKF and Ensemble Kalman Filter Reichle et al. (2008, 2002).

In the framework of the European Land Data Assimilation Systems (ELDAS, van den Hurk , 2002), and based on the approach proposed by (Hess, 2001), ECMWF developed a point-scale simplified EKF to analyse soil moisture (Seuffert et al., 2004). Based on local scale analysis experiments using the Southern Great Plains (SGP) 1997 field experiment data set Seuffert et al. (2004) showed that the OI and the EKF soil moisture analysis give similar results when they both use screen level parameters. They showed that the simplified EKF allows to combine screen level parameters with passive microwave brightness temperature data to analyse soil moisture.
The ECMWF simplified EKF was implemented to analyse soil moisture at global scale in the research version of the Integrated Forecasting System (IFS) by Drusch et al. (2009). Preliminary experiments were conducted to compare the OI and the simplified EKF to analyse soil moisture at global scale. To ensure a fair comparison between the OI and the simplified EKF, the analysis was set up to use 6-hour assimilation windows that match the OI analysis at fixed synoptic times. Although experiments were conducted for a relatively short 1-month period (May 2007) and at coarse resolution (125km), results showed that the EKF analysis (i) provided lower analysis increments, which were found to be more realistic, (ii) provided different amplitudes of the gain for the different soil layers, which are in better agreement with the physics governing the key hydrological processes, and (iii) showed a neutral impact on the global mean 2-metre temperature first guess. However, the computational costs in that specific experimental set up were three orders of magnitudes larger than for the OI making the surface analysis almost as expensive as the upper air 4D-var analysis. Since an advanced and flexible surface analysis system, which can make optimal use of current and future satellite operations, has been considered an important development of the IFS the surface analysis structure has been revised to separate the surface analysis from the upper air analysis.

This paper presents the operational implementation of the new surface analysis in the Integrated Forecasting System, including the simplified EKF based soil moisture analysis and the revised structure of the surface analysis. Results for the performance analysis and verification are presented for a set of one-year long analysis experiments. The forecast scores of atmospheric and soil moisture variables is investigated.

The capabilities for the inclusion of novel observation types is demonstrated using soil moisture data derived from the ASCAT sensor.

Section 2 describes the ECMWF land surface analysis system. Suitable sources of data that can be used to analyse soil moisture are discussed. The ECMWF land data assimilation system and the simplified EKF used to analyse soil moisture are presented, including the operational implementation. Section 3 describes numerical experiments conducted to evaluate the simplified EKF over a one-year period. Section 4 presents the results and discusses the impact of the simplified EKF on soil moisture and low level atmospheric forecasts. Conclusions and perspectives are given in the final section of the paper.

2 The ECMWF Land Surface Analysis System

2.1 The Land Surface Model HTESSEL

In the operational IFS, land surface processes are represented by HTESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land, Balsamo et al., 2009). HTESSEL represents soil moisture vertical movements using equations of Richards (1931). The soil column is discretised on four layers of thicknesses of 0.07, 0.21, 0.72 and 1.89m from top to bottom. Compared to the previous TESSEL LSM (Viterbo and Beljaars , 1995) used operationally at ECMWF until November 2007, HTESSEL accounts for global soil texture, based on the FAO (Food and Agriculture Organization) Digital Soil Map. For each model grid point, dominant soil texture is used to define soil hydraulic properties that control vertical movements of water in the soil. In addition a variable infiltration capacity was introduced to represent the fast component of surface runoff in November 2009, as described in Balsamo et al. (2009). The HTESSEL soil moisture parameterisation improved both the 2-metre temperature and soil moisture analysis. H-TESSEL also accounts for vegetation sub-grid scale variability, based on Global Land Cover Characteristics (GLCC) data. In November 2010, H-TESSEL was further improved to account for the Leaf Area Index seasonal cycle Boussetta et al. (2011) using a satellite-based monthly Leaf Area Index climatology.
The experiments conducted in this paper use the IFS cycle 36r1, implemented in January 2010. A detailed description of HTESSEL, as used for this paper, is given in ECMWF (2010).

2.2 Sources of data suitable for soil moisture analysis

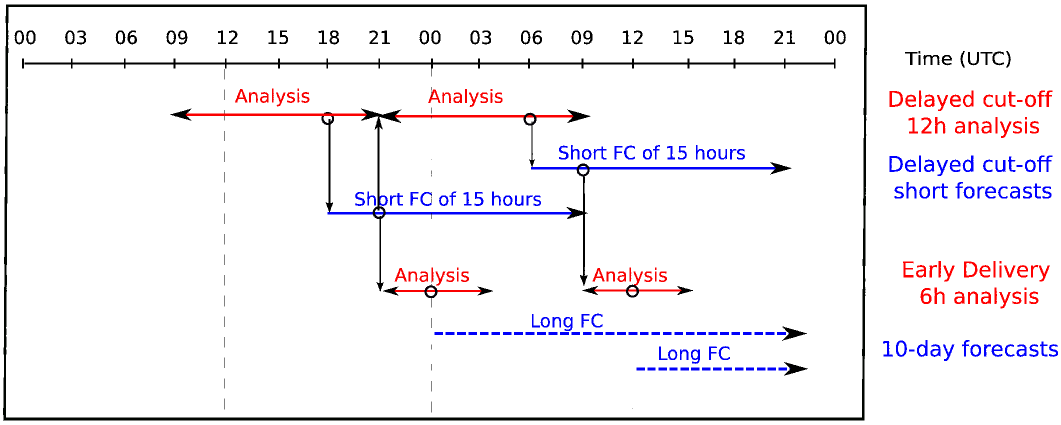
Most of current operational soil moisture analysis systems rely on analysed screen-level variables (2-metre temperature and relative humidity). In the absence of a near-real time global network for providing soil moisture information, using screen-level data is the only source of information that has been continuously available in real time for NWP soil moisture analysis systems. As shown by Douville et al (2000) and Mahfouf (1991), screen level parameters provide indirect, but relevant information to analyse soil moisture. In the past few years several new space-borne microwave sensors have been developed that give a more direct information on surface soil moisture.

The European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) mission was launched in 2009 (Kerr et al., 2010). Based on L-band passive microwave measurements, SMOS is the first mission dedicated to providing information about soil moisture globally at about 40km resolution. SMOS brightness temperatures have been monitored at ECMWF in near-real time since November 2010, as described

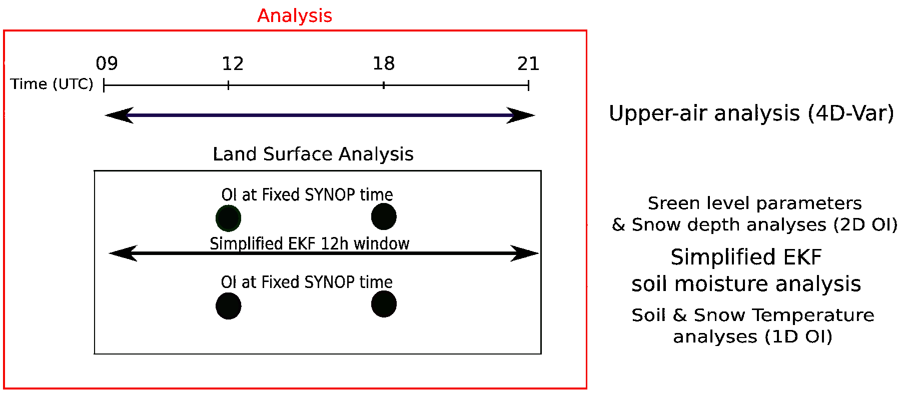
by Muñoz Sabater et al. (2011). Using the Community Microwave Emission Model (de Rosnay et al., 2009; Drusch et al., 2009), simulated brightness temperatures are compared with observed SMOS data and statistics are produced in near-real time. The future NASA SMAP (Soil Moisture Active and Passive) mission, planned to be launched in 2014, will combine active and passive L-band microwave measurements to provide global soil moisture and freeze/thaw state at high resolution (about 10km) (Entekhabi et al., 2010). It will ensure a good continuity with the current SMOS and high resolution products from SMAP are expected to be relevant for NWP applications.
The C-band active sensor ASCAT on MetOp was launched in 2006. The EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) ASCAT surface soil moisture product is the first operational soil moisture product (Bartalis et al., 2007). It is available in near-real time on EUMETCast (which is the EUMETSAT near-real time dissemination system) and it has been monitored operationally at ECMWF since September 2009. The near-real time and operational availability of the ASCAT soil moisture product makes it possible to use it for a large range of investigations in hydrology (Draper et al., 2011; Brocca et al., 2010) and soil moisture data assimilation for NWP and climate models initialisation (Mahfouf , 2010). At the United Kingdom Meteorological Office (UKMO), Dharssi et al. (2011) investigated ASCAT surface soil moisture data assimilation using a simple nudging scheme, as already used at the UKMO to analysis soil moisture from screen level parameters information. They showed that assimilating ASCAT data in addition to screen level information in their nudging scheme, improves soil moisture analysis and forecasts scores of screen level parameters in the tropics, in Australia and in North America. Based on their positive evaluation results ASCAT soil moisture nudging was implemented in operations in July 2010 at the UKMO. However since their assimilation system is based on a nudging approach, it will be difficult to combine different types of observations optimally.
At ECMWF Scipal et al. (2008) also investigated the impact of ASCAT soil moisture data assimilation in a simple nudging scheme. They showed that, compared to the model "open-loop" (without data assimilation), ASCAT soil moisture data assimilation improves the model soil moisture and screen level parameters. However they found that compared to the OI soil moisture analysis, ASCAT soil moisture nudging scheme has a slightly negative impact on the atmospheric forecasts. This due to the fact that the OI analysis was specifically designed to correct surface heat fluxes and screen level forecasts Drusch and Viterbo (2007); Mahfouf et al. (2000). So, Scipal et al. (2008) recommended using ASCAT data in an EKF analysis to account for observation errors and to optimally combine ASCAT data with screen-level information.

2.3 ECMWF Land Data Assimilation System

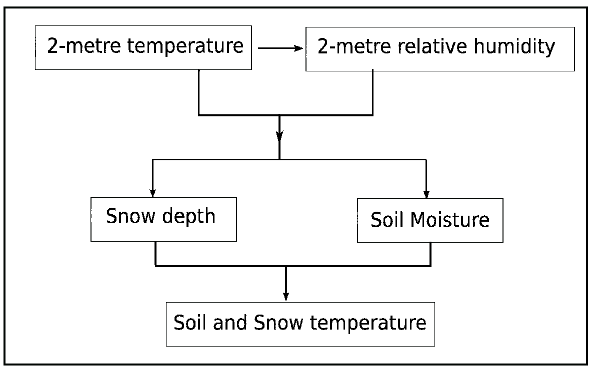
The ECMWF operational suite relies on an early delivery configuration that was implemented in 2004, as described in Haseler (2004). Figure 1 gives a schematic representation of the current surface analysis structure in the ECMWF operational suite. The early delivery analyses (Figure 1, a) are produced twice daily with an about 4-hour cut-off time for observations. They use 6-hour data assimilation windows from 0900 UTC to 1500 UTC and from 2100 UTC to 0300 UTC, respectively. They are used to initialise the 10-day forecasts (Haseler, 2004).
The early delivery analyses rely on a delayed cut-off analysis system, which is based on two 12-hour data assimilation windows (two cycles) per day, performed from 2100 to 0900 UTC and from 0900 to 2100 UTC, respectively. Delayed cut-off analyses are run with a 14-hour cut-off time for observations that allows to use more observations than in the early delivery analyses. For each analysis cycle, a short 15-hour forecast initialised from the delayed cut-off nalysis provides the background information for the next cycle of both delayed cut-off and early delivery analyses. The short forecasts ensure the information



(a) Early Delivery Configuration of the ECMWF operational suite implemented in 2004 (from Haseler, 2004).



(b) Analysis tasks (example for the 0900 UTC to 2100 UTC 12h window).



(c) Dependencies between surface analysis tasks

Figure 1: Operational Early delivery suite (a), from Haseler (2004) and surface analysis implementation (b and c) within the Early delivery suite.

propagation from cycle to cycle and they are used to initialise the early delivery analyses of the next cycle (Haseler, 2004).

The ECMWF land data assimilation system includes the analyses of screen-level parameters (2-metre temperature and relative humidity), snow depth, soil moisture, soil temperature and snow temperature (see Figure 1, b) . Land surface analysis is performed separately from the upper air atmospheric analysis (4D-Var). The upper-air analysis and the land-surface analyses are used together as initial conditions for the first guess and the 10-day forecasts. So, the surface analysis feedbacks the upper-air analysis of the next cycle through its influence on the short forecast that propagates information from one cycle to the next (see Figure 1 b,c). Reciprocally, the 4D-Var influences through the first guess forecasts the land surface analysis from one cycle to the next. The OI analyses of screen level parameters, snow depth, snow and soil temperature are performed at synoptic times, 4 times per day at 0000, 0600, 1200, and 1800 UTC. The simplified EKF uses the window as the 4D-Var.

2.4 ECMWF simplified EKF soil moisture analysis

The simplified EKF implemented at ECMWF to analyse soil moisture is a point wise data assimilation scheme. Following the notation of Ide et al. (1997), the analysed soil moisture state vector $\mathbf{x}^a$ is computed at time t_i for each grid point as:

$$\mathbf{x^a}(\mathbf{t_i}) = \mathbf{x^b}(\mathbf{t_i}) + \mathbf{K_i}\left[\mathbf{y^o}(\mathbf{t_i}) - \mathscr{H}_{\mathbf{i}}(\mathbf{x^b})\right] \tag{1}$$

with superscripts a, b, o standing for analysis, background and observations, respectively. $\mathbf{x}$ is the model state vector, $\mathbf{y}$ is the observation vector and $\mathscr{H}$ the non-linear observation operator. The Kalman gain matrix $\mathbf{K}_i$ is computed at time t_i as:

$$\mathbf{K_i} = \left[\mathbf{B}^{-1} + \mathbf{H_i}^{\mathbf{T}}\mathbf{R}^{-1}\mathbf{H_i}\right]^{-1}\mathbf{H_i}^{\mathbf{T}}\mathbf{R}^{-1} \tag{2}$$

where $\mathbf{H_i}$ is the linearised observation operator, $\mathbf{B}$ is the approximate background error covariance matrix associated with $\mathbf{x}$ and $\mathbf{R}$ is the observation errors covariance matrix.

As described in Drusch et al. (2009) the background error covariance matrix $\mathbf{B}$ and the observation error matrix $\mathbf{R}$ are static, with diagonal terms composed of error variances. These terms are based on soil moisture standard deviation σ_b equal $0.01m^3m^{-3}$, screen levels parameters standard deviations σ_T equal $2K$ for the 2-metre temperature and σ_{RH} equal 10% for the relative humidity. However, the system can accommodate $\mathbf{R}$ and $\mathbf{B}$ matrixes that are variable in space and time to allow an optimal use of error structures in the model and the observations.

The linearisation of the observation operator is computed in finite differences, by using individual perturbations of the model state vector by a small amount δx_n of the n^{th} component of the model state vector. One perturbed simulation is required for each element of the control state vector. For each perturbed simulation, the initial background state vector is perturbed by a vector $\delta\mathbf{x_n^b}$ that contains δx_n for the perturbed n^{th} element and zero for all the other elements. Using index m to represent the m^{th} element of the observations vector, the Jacobian elements $\mathbf{H_{mn,i}}$ of the observation operator at time t_i can be written as:

$$\mathbf{H_{mn,i}} = \frac{\mathscr{H}_{\mathbf{m,i}}(\mathbf{x^b} + \delta\mathbf{x_n^b}) - \mathscr{H}_{\mathbf{m,i}}(\mathbf{x^b})}{\delta x_n} \tag{3}$$

The model state vector evolution from time t_i to time t_{i+1} is then defined as:

$$\mathbf{x}^b(t_{i+1}) = \mathcal{M}_\mathbf{i}\left[\mathbf{x^a}(\mathbf{t_i})\right] \tag{4}$$

with $\mathcal{M}$ the non-linear forecast model. Following Drusch et al. (2009) the soil moisture perturbations were set to $0.01m^3m^{-3}$.

In the current operational system, the state vector combines the soil moisture and it has dimension $n_{max} = 3$ since the first three layers of the HTESSEL LSM are analysed. The observations vector $\mathbf{y}$ includes the 2-metre temperature and relative humidity analyses. When 12-hour assimilation windows are used, $\mathbf{y}$ has dimension $m_{max} = 4$ since 2-metre temperature and relative humidity analyses are available twice per assimilation window, at synoptic times, as illustrated in Figure 1. It is the small dimension of the state vector that makes the method viable. Its advantage is that no adjoint and tangent linear model is required.

It is also possible to simultaneously assimilate screen-level observations and satellite data such as ASCAT surface soil moisture or SMOS brightness temperature products. In this paper, preliminary results of ASCAT data assimilation in the simplified EKF are presented along with screen level parameters assimilation results. Although ASCAT is not used in operations this aims at showing the feasibility of combining screen level and satellite information in the multi-variate simplified EKF. For ASCAT data assimilation, ASCAT soil moisture standard deviation was defined to be twice larger than the background soil moisture error.

2.5 Discussion on the simplified EKF implementation

Although the OI soil moisture analysis that was used in operations before the simplified EKF is limited in terms of both performance and flexibility in its use of different types of data, the OI system has the advantage of being simple and computationally inexpensive. At any resolution the OI CPU (Central Processing Unit) time consumption remains negligible, ranging from about 3 seconds CPU at 125 km (T159) to 20 seconds CPU for a 25 km resolution (T799) - note that all computing times given in this paper are based on the IBM power 6 High Performance Computing Facility used at ECMWF. In previous versions of the IFS (until IFS cycle 35r2) as used in Drusch et al. (2009), van den Hurk et al. (2008), van den Hurk (2002), the surface analysis was performed after the 4D-Var upper-air analysis. The surface analysis used the observations from the upper-air analysis observations data base and some of the surface analysis input fields (10-metre wind components and albedo) were outputs from the upper-air analysis. Hence, the surface analysis had to wait for the upper-air analysis to be completed. As a consequence the surface analysis had only a very limited time to be completed and only very simple land surface analysis systems were affordable for operations.

The simplified EKF is far more expensive than the OI to analyse soil moisture. For a resolution of 125km its time consumption is close to 3.10^3 seconds CPU. At 80km resolution (T255) it increases to 10^4 CPU seconds and it is close to 2.10^5 CPU seconds (one fifth of the 4D-Var time consumption) at 25km resolution (T799). In order to prepare the implementation of the EKF soil moisture analysis, a new surface analysis structure were implemented operationally in September 2009. The new structure removed any direct dependency between the surface analysis and the upper-air 4D-Var analysis. The observational dependency was resolved by creating a new observation data base dedicated to surface analysis. The field dependency issue was resolved by using, as input of the land surface assimilation system, the first guess fields instead of the upper-air analysis output fields. Because the new surface analysis and the upper-air analysis are separated they can be run independently of each other using the available CPU time in each analysis cycle more efficiently.

The new surface analysis structure enabled the operational implementation of the simplified EKF soil moisture analysis in November 2010. The simplified EKF is used in operations at a resolution of 16 km (T1279), using the same number of processors and threads as the upper-air analysis. In this configuration, the soil moisture analysis based on the simplified EKF takes a wall-clock time of 750 seconds (7.10^5 CPU seconds) and finishes before the the upper-air analysis.

3 Experiments

To evaluate the performance of the EKF soil moisture analysis three analysis experiments were conducted at 80km resolution (T255) over a one-year period, from 01 December 2008 to 30 November 2009: (i) The "OI" experiment represents the control. The OI soil moisture analysis uses the increments of the screen-level parameters analysis as input and a statistically based gain matrix. It represents the operational soil moisture analysis configuration that was used in operations at ECMWF from July 1999 to November 2010 and described in Mahfouf et al. (2000). (ii) The "EKF" experiment uses a dynamical gain matrix obtained with the simplified EKF described in the previous section, in which the analysis of screen-level parameters is used as proxy information for soil moisture. (iii) In the "EKF+ASCAT" experiment, the screen-level parameters analysis is used together with the ASCAT soil moisture data in the multi-variate simplified EKF. In this "EKF+ASCAT" experiment, ASCAT soil moisture data is matched to the ECMWF IFS model soil moisture using a Cumulative Distribution Function (CDF) matching as described in Scipal et al. (2008). The first demonstration of the impact of using a nudging scheme to assimilate ASCAT data has already been performed by Scipal et al. (2008). They showed, however, that compared to the OI system, using scatterometer data slightly degraded the forecast scores. The "EKF+ASCAT" experiment, is a preliminary investigation of combined screen level parameters and ASCAT soil moisture data assimilation in the simplified EKF.
Note that the "OI" and "EKF" experiments only differ in the method used for the soil moisture analysis. The key difference between the two approaches is in the Kalman gain matrix computation. The EKF coefficients are dynamically estimated, so the soil moisture corrections are expected to account for meteorological forcing (radiative and precipitation) and soil moisture conditions. The "OI" and the "EKF" experiments use the same observations. The "EKF+ASCAT" experiment uses ASCAT satellite data in addition to conventional data.
One month of analysis spin-up is considered for the first month of each experiment, so results presented here focus on the period January to November 2009.

4 Results and discussion

4.1 Soil Moisture increments

Figure 2 shows monthly accumulated soil moisture increments for the first metre of soil for January (left) and for July (right) 2009 for the OI (top panel) and simplified EKF (middle panel) experiments, and their difference in absolute value (bottom panel). In January, the OI and the simplified EKF analysis

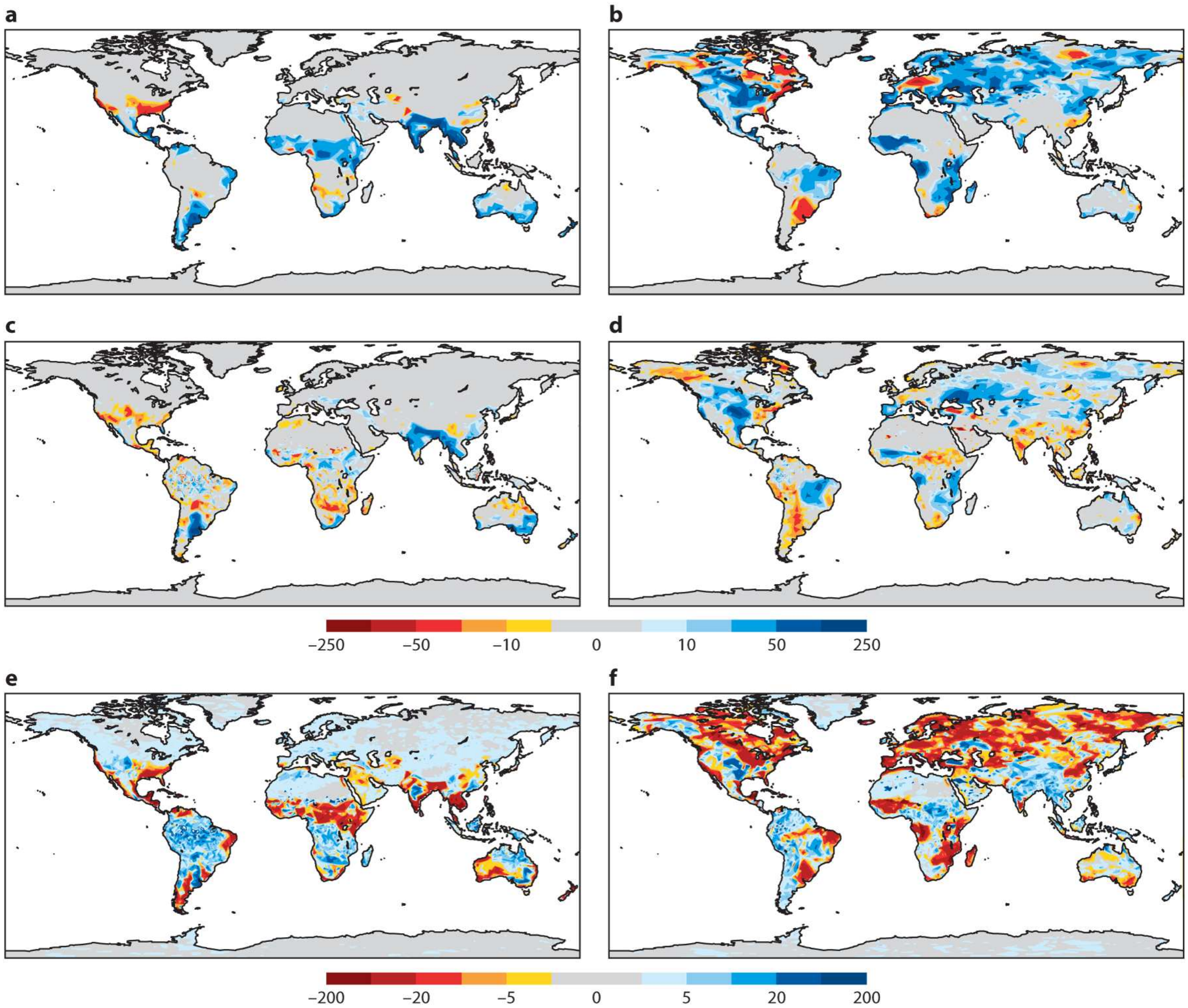


Figure 2: Soil moisture analysis increments, in mm, accumulated for January (left) and July (right) 2009 for the OI experiment (top), the simplified EKF experiment (middle) and difference of absolute values of soil moisture increments of the simplified EKF and the OI experiments (bottom).

increments present similar spatial patterns, with positive increments over India, west Africa, Argentina, south-east Australia and negative increments in North America. However increments are much reduced with the simplified EKF compared to the OI. In July, soil moisture increments are larger than in January in the northern hemisphere. Comparison between January and July shows that the analysis is most active in the summer hemisphere, due to stronger coupling between soil moisture and screen level in summer conditions. In July increments are generally positive in most areas for both the OI and the simplified EKF. However, negative increments are found in Argentina, Alaska and north east of America. Both in January and in July, the simplified EKF reduces the soil moisture analysis increments compared to the OI scheme.

Figure 3 shows the difference of absolute values of soil moisture increments between the simplified EKF and the OI for the top soil layer (0-7cm), the middle layer (7-28cm) and the bottom layer (28cm-100cm). Analysis increments of the simplified EKF are much reduced compared to those of the OI in the second and third soil layers. The OI increments are large in the deeper soil layers because they are computed in

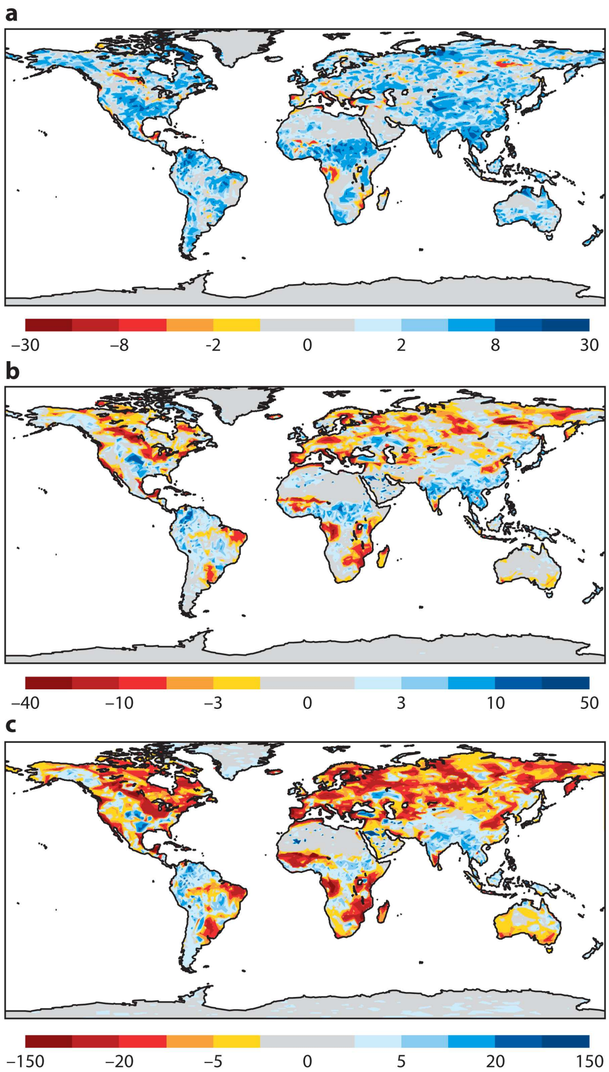


Figure 3: Difference of absolute values of soil moisture increments, in mm accumulated for July 2009, between the simplified EKF and the OI experiments for the top soil moisture layer (0-7cm, top), second layer (7-28cm, middle) and bottom layer (28-100cm, bottom).

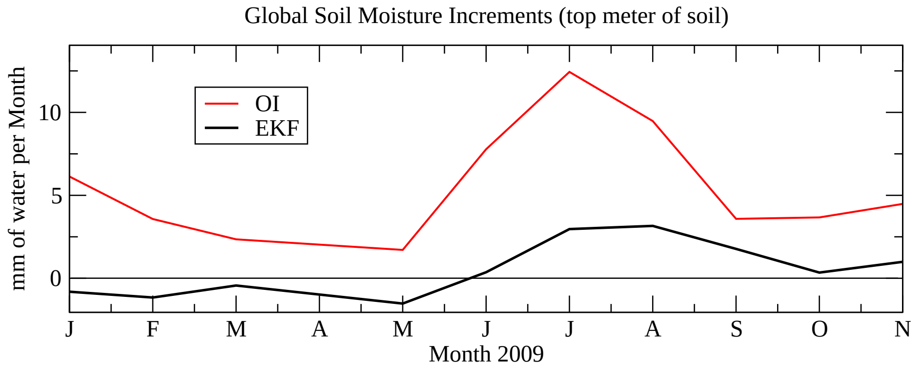


Figure 4: Temporal evolution of soil moisture increments in the first metre of soil (global mean value) in mm of water per month from January 2009 to November 2009, produced by the OI and the simplified EKF.

volumetric values for the surface soil layer and simply converted into water equivalent according to the different soil layer thicknesses. For the OI, this leads to unrealistically large increments in these layers. The simplified EKF soil moisture increments result from the Jacobians computation (Equation 3) which is performed separately for each analysed soil layer. The Jacobians account for the weaker relationship of the screen level parameters with deep soil moisture than with the surface soil moisture layer that contains most of the roots. This explains the large reduction of analysis increments in the third layer. In contrast soil moisture increments are larger at the surface with the simplified EKF than with the OI. So, compared to the OI system, the simplified EKF has a different vertical distribution of the soil moisture increments, with larger increments near the surface, indicating a relatively stronger coupling between surface soil moisture and atmosphere.

Figure 4 shows the annual cycle of the global mean soil moisture increments for the OI and simplified EKF experiments. It shows that the soil moisture increments of the OI scheme systematically add water to the soil, as discussed in the past by van den Hurk et al. (2008). The global mean value of the OI analysis increments is 5.5 mm per month, which represents a substantial and unrealistic contribution to the global water cycle. In contrast the simplified EKF global mean soil moisture analysis increments are much smaller, representing global mean increments of 0.5 mm per month. The reduction of increments between the simplified EKF and the OI is mainly due to the reduction in increments for the deeper soil layers. The OI increments computed for the first layer are amplified for deeper layers in proportion to the layer thickness, explaining the overestimation of OI increments. In contrast the simplified EKF dynamical estimates, based on perturbed simulations, allow the optimising of soil moisture increments at different depths to match screen-level observations according to the strength of the local and current soil-vegetation-atmosphere coupling. The simplified EKF allows for additional controls due to meteorological forcing and soil moisture conditions. So, it prevents undesirable and excessive soil moisture corrections.

4.2 Impact on soil moisture analysis and forecast

Soil moisture analysis and forecasts were evaluated for December 2008 to November 2009 against the 12 SMOSMANIA (Soil Moisture Observing System - Meteorological Automatic Network Integrated Application) ground stations of Météo-France (Albergel et al., 2008; Calvet et al., 2007). The SMOS-

Table 1: Mean correlation values, for December 2008 to November 2009, between ECMWF soil moisture and SMOSMANIA ground data, for the OI and the EKF experiments, for the analysis, 24-hour and 48-hour forecasts.

Experiment	Analysis	24-hour forecast	48-hour forecast
OI	0.80	0.72	0.72
EKF	0.84	0.77	0.77
EKF+ASCAT	0.84	0.78	0.77

MANIA network is located in south west France. It spans more than 3.5° in latitude between 0.85°W and 2.96°E and 1° in latitude, between 43.15°N and 44.15°N. A large diversity of weather and ground conditions occur for the SMOSMANIA network, from oceanic condition in the western part to Mediterranean conditions in the south east part of the network. So, SMOSMANIA is very useful for evaluating soil moisture products (e.g. Albergel et al., 2012; Parrens et al., 2010; Albergel et al., 2010).
Table 1 shows mean correlation values between ECMWF surface soil moisture and ground data over the SMOSMANIA network, for the analyses, 24-hour and 48-hour forecasts for the "OI", "EKF" and "EKF+ASCAT" experiments. This table shows that both soil moisture analysis and forecasts are in very good agreement with the ground data. Mean correlation for the OI analysis is 0.8. It is improved to 0.84 when the simplified EKF is used. Using ASCAT soil moisture data ("EKF+ASCAT") does not improve the correlation with the ground data. Forecasts scores at 24-hour range are degraded compared to the analysis, they still indicate that using the simplified EKF analysis improves the agreement with ground data, with mean correlation value of 0.77 for the "EKF" experiment. The decay in correlation values in the short range forecast (e.g. 0.84 to 0.72 in the first 24-hour for the "EKF" experiment) is related to the rapid decrease in precipitation scores in the short range (Lopez , 2011). While precipitation data assimilation leads to significant improvements in the first 12 hours of the forecast, this improvement vanishes for ranges beyond 24 hours Lopez (2011). In contrast it is interesting to notice that the impact of the simplified EKF on the soil moisture forecast is persistent between 24-hour and 48-hour forecasts. This highlights the complementarity of combined precipitation and soil moisture data assimilation. This may be even more important for longer assimilation windows that one now is being investigated for the 4D-Var atmospheric analysis.

Figure 5 shows the impact of the soil moisture analysis scheme on the 48-hour forecast soil moisture of the first soil layer for all three experiments. It confirms that ECMWF soil moisture 48-hour forecast is generally in good agreement with ground observations, with mean correlations higher than 0.7 in any configuration of the soil moisture analysis. With the OI, ECMWF 48-hour forecast correlation with ground data is lower than 0.7 for three stations (out of 12). In contrast, correlation lower than 0.7 is obtained only for two stations with the simplified EKF.

For seven stations, correlation between ECMWF 48-hour forecast and soil moisture observation is equal or higher than 0.8 when the simplified EKF is used, with or without ASCAT assimilation. Correlation value higher than 0.8 is obtained for only one station in the OI configuration. Figure 6 shows a scatter plot of correlation values obtained for the EKF and EKF+ASCAT against the OI configurations. These results show that using the simplified EKF instead of the OI scheme to initialise soil moisture conditions improves significantly the soil moisture forecasts performances, leading to a remarkable agreement between ECMWF soil moisture and ground truth.

Results obtained from the "EKF+ASCAT" experiment show that using ASCAT does not improve the performance of the soil moisture analysis significantly. In the experiment where ASCAT data is assimilated, soil moisture data has been rescaled to the model soil moisture climatology using a CDF matching,

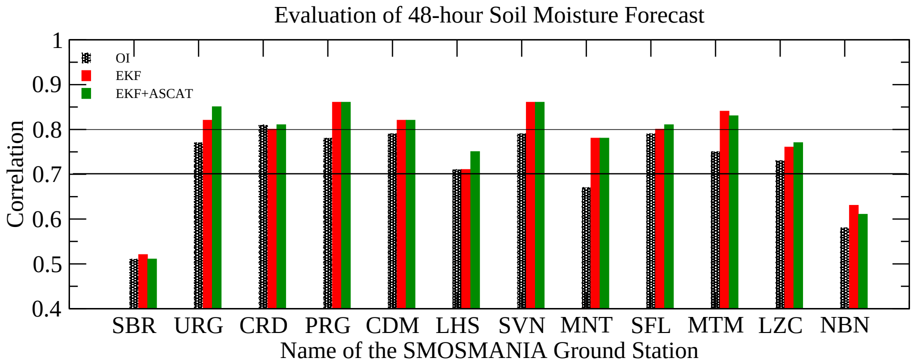


Figure 5: Correlation values between 48-hour forecasts of ECMWF soil moisture for the 12 stations of the SMOSMANIA network (Soil Moisture Observing System - Meteorological Automatic Network Integrated Application) in Southwest of France, for the OI, the EKF and EKF+ASCAT configurations of the soil moisture analysis.

as described in Scipal et al. (2008). The matching corrects observation bias and variance. So, in the data assimilation scheme only the observed ASCAT soil moisture variability is assimilated. In Figures 5 and 6, the impact of ASCAT data assimilation might be limited by both the quality of the current ASCAT product and the CDF-matching approach used in the assimilation scheme. EUMETSAT recently revised the processing of the ASCAT soil moisture product to reduce the ASCAT product noise level. Future experiments using an improved CDF-matching, with HTESSEL corrected from precipitation errors, and improved data quality are expected to enhance the impact of using ASCAT soil moisture in the data assimilation.

To investigate the ability of soil moisture forecasts to capture small time scale soil moisture variations, soil moisture anomaly time series, based on a 5-week moving window, as described in Albergel et al. (2012), were evaluated. While correlation of soil moisture times series are, to a large extend driven by the annual cycle, anomaly correlation values relate the agreement of soil moisture short term variability. Results of soil moisture forecasts anomaly time series validation against ground data are presented in Figure 7 for winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November). Compared to Figure 6, Figure 7 shows that anomaly correlation values are generally lower than correlation values. It also shows that the impact of the EKF is less important on anomaly time series than on annual cycle time series, with most of the point very close to the median line, indicating a rather neutral impact in terms of soil moisture anomaly time series improvements. Largest improvement of the EKF compared to the OI is obtained in summer (triangles) for a total of six stations.

4.3 Impact on the 2-metre temperature first guess and forecasts

Figure 8 shows, for July 2009, the global impact of the EKF on the 2-metre temperature first guess for all the synoptic times (00 UTC, 06 UTC, 12 UTC, 18 UTC). The EKF soil moisture analysis scheme slightly improves the 2-metre temperature scores by consistently reducing the root mean square error (RMSE) of the first guess from 2.2 K for the "OI" experiment to 2.17 K for the "EKF" experiment. This figure shows that the first guess error is largely affected by a diurnal cycle which is related to (i) the spatial distribution of the SYNOP reports, with more observations in Europe than in other continents and (ii)

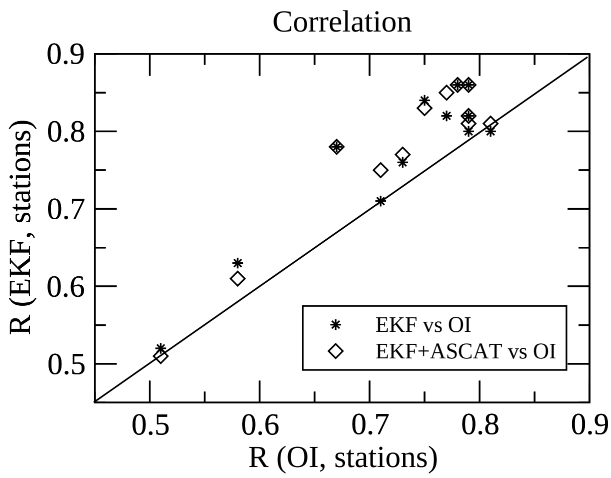


Figure 6: Comparison of the 48-hour forecast soil moisture performance for the EKF against the OI configurations of the soil moisture analysis. As in Figure 5), performance is quantified as the correlation between the forecast and ground observations. Each point represent correlation values obtained for a SMOSMANIA station for December 2008 to November 2009. Comparison between EKF (EKF+ASCAT) and OI performances is represented by stars (diamonds).

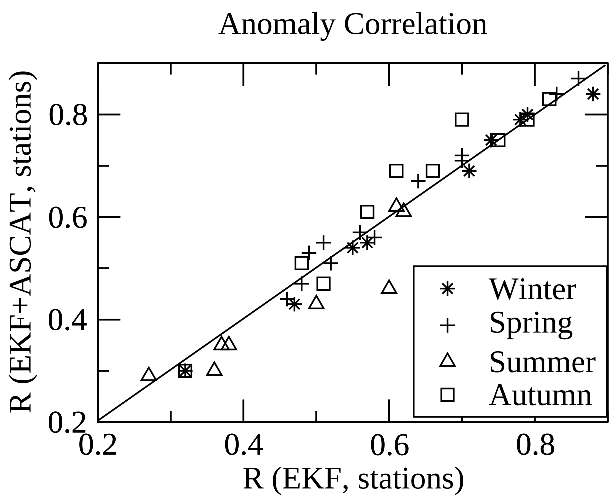


Figure 7: Comparison of the 48-hour forecast soil moisture anomaly performance for the EKF against the OI configuration. Forecast performance is quantified by computing correlation values between soil moisture anomaly times series (base on 5-weeks moving window) between the 48-hour forecasts and ground measurements for each stations of the SMOSMANIA network and for each season. Scores in Winter (DJF) are represented by starts, in spring (MAM) by crosses, in summer (JJA) by triangles and in autumn (SON) by squares.

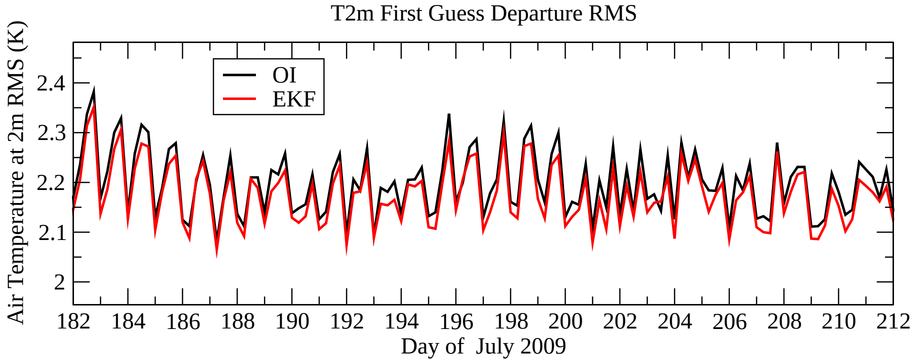


Figure 8: Root mean square difference between 2-metre temperature observations and model first guess for July 2009, with the OI (black) and the simplified EKF (red) soil moisture analyses.

Table 2: RMSE and bias of 2-metre temperature (in K) against SYNOP observations at global scale for January to November 2009 for first guess (FG) and analyses (AN) for the "OI" and the "EKF" experiments.

Experiment	RMSE FG	Bias FG	RMSE AN	Bias AN
OI	2.27	0.50	1.60	0.06
EKF	2.25	0.44	1.60	0.06

the first guess range which is either a 6-hour forecast (for the 00 UTC and 12 UTC analysis) or a 12-hour forecast (for the 18 UTC and the 06 UTC analyses). Table 2 shows 2-metre temperature RMSE and bias against SYNOP observations, for January to November 2009. While the simplified EKF has a neutral impact on the 2-metre temperature analysis, it has a clear positive impact on the 2-metre temperature short-range forecast, with first guess 2-metre temperature RMSE being 2.27 K for the "OI" and 2.25 K for the "EKF", and bias values of 0.5 K and 0.44 K for the "OI" and the "EKF", respectively.

Figure 9 shows the monthly mean impact of the simplified EKF soil moisture analysis on the 48-hour forecast of 2-metre temperature at 0000 UTC for January (top) and July (bottom) 2009. It indicates the difference in temperature error (in K) between the OI and EKF experiments. Positive values indicate that the EKF generally improves the 2-metre temperature forecasts compared to the OI soil moisture analysis. In most areas the 2-metre temperature errors are larger for the OI than for the simplified EKF. This confirms the positive impact of the simplified EKF soil moisture analysis on the 2-metre temperature forecast at 48-hour range.

5 Conclusions and Perspectives

Although a large number of satellites observations describing the state of the land surface has been available for decades now, hardly any of this information has been used in operational analysis systems in an optimal way, i.e. taking the individual error characteristics into account. In November 2010 a new surface analysis system based on a simplified Extended Kalman Filter was operationally implemented in the ECMWF Integrated Forecasting System. It is fully flexible in that new observation types can be easily integrated and different surface variables, e.g. soil moisture, soil temperature and snow water equivalent, could be analysed consistently. The analysis system has first been introduced for the soil moisture anal-

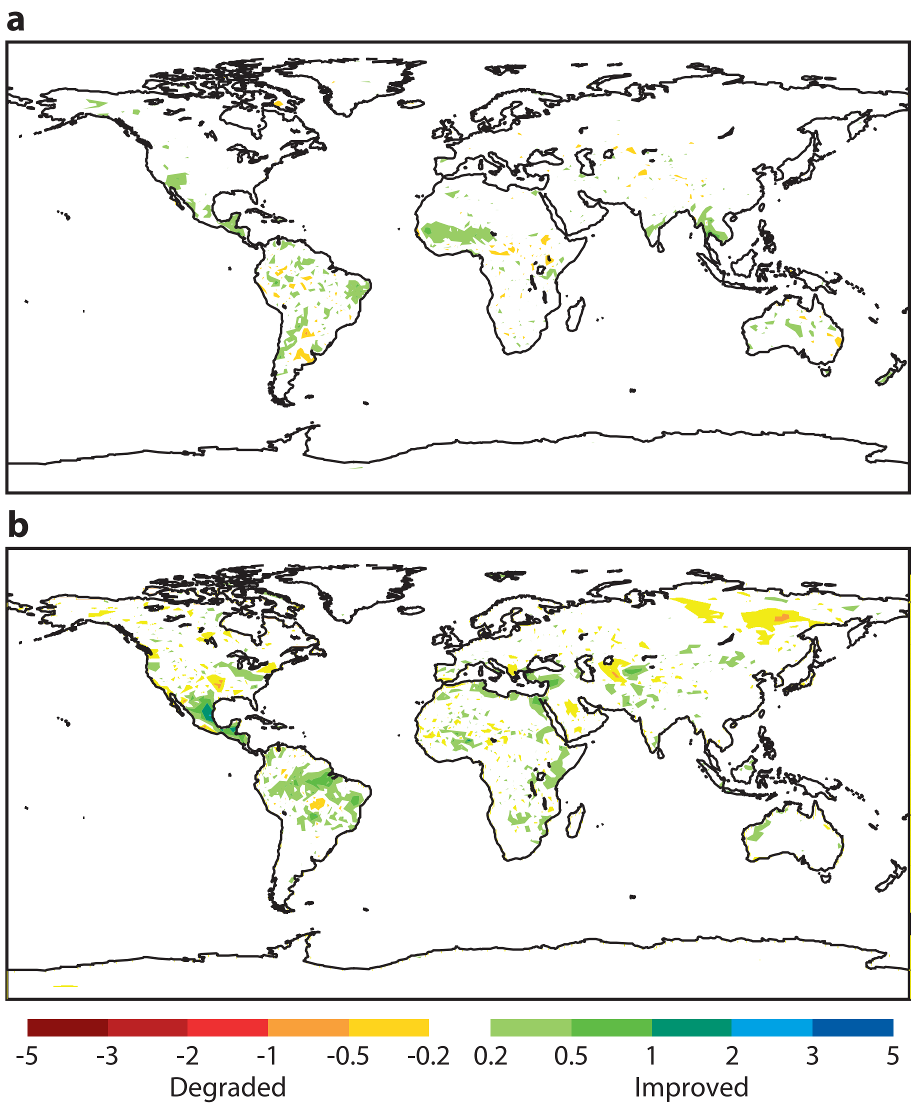


Figure 9: Monthly mean difference for January 2009 (top) and for July 2009 (bottom) between the errors in the 48-hour forecasts (0UTC) of 2-metre temperature (in K) for the OI and the EKF soil moisture analysis scheme. The forecasts are verified against the operational analysis.

ysis for the top three soil layers. Compared to the previous OI scheme, the EKF is a dynamical scheme that accounts for non-linear influence of meteorological forcing and soil moisture conditions on the soil moisture increments. So, it prevents undesirable and excessive soil moisture corrections, and reduces the soil moisture analysis increments. This significantly improves the performance of the soil moisture analysis and forecasts, as verified against independent soil moisture observations. The new analysis scheme has a moderate impact on the atmospheric scores although it slightly improves the 2-metre temperature by reducing the cold bias in Europe and Africa. The simplified EKF enables the combined use of screen-level parameters and satellite data, such as ASCAT soil moisture data, to analyse soil moisture. While the results with ASCAT data assimilation show a neutral impact on both soil moisture and screen-level parameters, recent improvements in the ASCAT soil moisture products and in bias correction are expected to enhance the impact of using ASCAT in the soil moisture analysis. The new land surface analysis structure and the EKF method open a wide range of further development possibilities, including exploiting new satellite surface products, such as SMOS and the future SMAP data. An extension of the EKF to analyse additional variables, such as snow mass and vegetation parameters, will also be investigated in the near future.

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