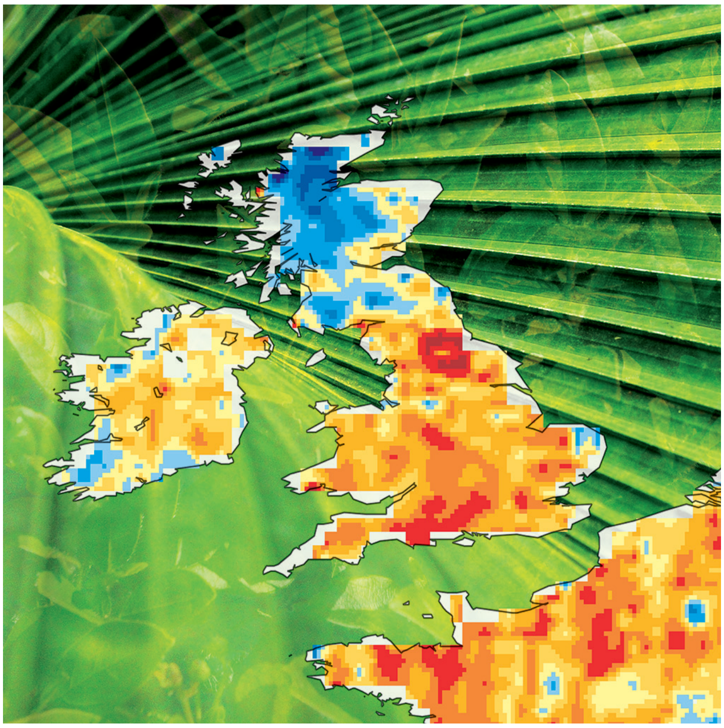
ECMWF Feature article

from Newsletter Number 127 – Spring 2011

METEOROLOGY

Extended Kalman Filter soil-moisture analysis in the IFS



www.ecmwf.int/en/about/news-centre/media-resources

doi:10.21957/ik7co53s

This article appeared in the Meteorology section of ECMWF Newsletter No. 127 – Spring 2011, pp. 12–16.

Extended Kalman Filter soil-moisture analysis in the IFS

Patricia de Rosnay, Matthias Drusch, Gianpaolo Balsamo, Clément Albergel, Lars Isaksen

A new soil moisture analysis scheme based on a point-wise Extended Kalman Filter (EKF) was implemented at ECMWF with cycle 36r4 of the Integrated Forecasting System (IFS) in November 2010. The EKF soil moisture analysis replaces the previous Optimum Interpolation (OI) scheme, which was used in operations from July 1999 (IFS cycle 21r2) to November 2010. In continuity with the previous system it uses 2-metre air temperature and relative humidity observations to analyse soil moisture. The computing cost of the EKF soil moisture analysis is significantly higher than that of the OI scheme. So, as part of the EKF soil moisture analysis implementation, a new surface analysis structure was implemented in September 2009 (cycle 35r3) to move the surface analysis out of the time critical path.

The main justifications for implementing the EKF soil moisture analysis are as follows.

- In contrast to the OI scheme, which uses fixed calibrated coefficients to describe the relationship between an observation and model soil moisture, the EKF soil moisture increments result from dynamical estimates that quantify accurately the physical relationship between an observation and soil moisture.
- The EKF scheme is flexible to cope with the current increase in model complexity. In particular, changes in the IFS and in the land-surface model H-TESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land) are accounted for in the analysis increments computation.
- The EKF soil moisture analysis makes it possible to use soil moisture data from satellites and to combine different sources of information (i.e. active and passive microwave satellite data, and conventional observations).
- It considers the observation and model errors during the analysis in a statistically optimal way and allows assimilation of observations at their correct observation times.

The implementation and evaluation of the EKF soil moisture analysis is described in this article. An overview is given of a set of one-year analysis experiments conducted to assess the performance of the EKF. These experiments led to the implementation of the EKF in November 2010 using screen-level parameters to analyse soil moisture. The impact of ASCAT (Advanced SCATterometer) data assimilation is also briefly presented to investigate the possibility to combine conventional observations and satellite data for the soil moisture analysis.

Sources of data

The ECMWF operational soil moisture analysis system is based 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 for NWP soil moisture analysis systems. It provides indirect, but relevant information to analyse soil moisture.

In the past few years several new space-borne microwave sensors have been developed that measure soil moisture. They provide spatially integrated information on surface soil moisture at a scale relevant for NWP models.

- The active sensor ASCAT on MetOp was launched in 2006. The EUMETSAT ASCAT surface soil moisture product is the first operational soil moisture product. It is available in near-real time on EUMETCAST and it has been monitored operationally at ECMWF since September 2009.
- ESA's SMOS (Soil Moisture and Ocean Salinity) mission was launched in 2009. Based on L-band passive microwave measurements, SMOS is the first mission dedicated to providing information about soil moisture.
- The future NASA SMAP (Soil Moisture Active and Passive) mission, planed to be launched in 2015, will be a soil moisture mission that combines active and passive microwave measurements to provide global soil moisture and freeze/thaw state.

 doi:10.21957/ik7co53s

ECMWF plays a major role in developing and investigating the use of new satellite data for soil moisture analysis. For example, the EUMETSAT ASCAT soil moisture product has been monitored operationally at ECMWF since September 2009 and SMOS brightness temperature product has been monitored in near-real time since November 2010:

- http://www.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/slmoist/ascat/
- http://nwmstest.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/smos

Implementation of SMOS data monitoring at ECMWF is described in an accompanying paper by *Muñoz Sabater et al.* in this edition of the *ECMWF Newsletter* (pages 23–27).

The ECMWF land-surface analysis system

The ECMWF land-surface analysis includes the analysis of snow depth, screen-level parameters (2-metre temperature and relative humidity) as well as soil moisture and soil temperature. It is performed independently from the 4D-Var atmospheric analysis. The upper-air analysis and the land-surface analysis are used together as initial conditions for the forecast. In turn, the model-predicted fields provide the first guess and initial conditions of the next land-surface and upper-air analysis cycle. So, surface analysis indirectly interacts with the upper-air analysis of the next cycle through its influence on the forecast that propagates information from one cycle to the next.

The surface analysis is performed at fixed times at 0000, 0600, 1200, and 1800 UTC. With the re-structured surface analysis it is able to run at the same time as the two main 12-hour windows used in the 4D-Var atmospheric analyses; these cover the periods from 2100 to 0900 UTC and from 0900 to 2100 UTC.

The soil moisture analysis is based on the analysis of screen-level parameters which provides gridded information on 2-metre temperature and relative humidity. So, screen-level SYNOP data is used as proxy information for the soil moisture analysis, based on the relationship between soil variables (moisture and temperature) and the near-surface atmosphere controlled by evaporation processes.

With the OI soil moisture analysis, soil wetness and 2-metre temperature (relative humidity) increments were assumed to be negatively (positively) correlated.Therefore the 2-metre analysis increments of temperature and relative humidity were used as input for the soil moisture OI scheme as described in *Mahfouf* (2000). Soil moisture analysis increments were computed analytically for each model grid point for the four soil moisture layers of the land-surface model H-TESSEL. The OI soil moisture analysis scheme improved the boundary layer forecasts skill, but not soil moisture in which errors were allowed to accumulate, as shown in *Drusch et al.* (2008).

In order to improve the use of conventional observations and enable use of land-surface satellite measurements, an advanced surface data assimilation system, based on an Extended Kalman Filter (EKF) approach, was developed by *Drusch et al.* (2008). With this approach, the EKF coefficients are dynamically estimated, so the soil moisture corrections account for meteorological forcing (radiative and precipitation) and soil moisture conditions. There is also the possibility of simultaneously assimilating screen-level observations and satellite data such as ASCAT surface soil moisture or SMOS brightness temperature products. The EKF soil moisture analysis is a point wise data assimilation scheme – the scheme used at ECMWF is outlined in Box A.

EKF soil-moisture analysis scheme

A

For each grid point, the analysed soil moisture state vector θ_a is computed as:

$$\theta_a = \theta_b + K(y - H\,\theta_b)$$

with θ_b the background soil moisture state vector, H the Jacobian matrix of the observation operator, y the observation vector and K the Kalman gain matrix which accounts for the Jacobian matrix, and the covariance matrix of background and observation errors. In this system the observation vector can include:

- Conventional observations such as 2-metre temperature and relative humidity.
- Satellite measurements of soil moisture (e.g. ASCAT product) or any other measurement related to soil moisture (e.g. SMOS, brightness temperatures).

The elements of the Jacobian matrix used in the analysis scheme are estimated in finite differences by perturbing individually each analysed soil layer. In contrast to the OI scheme, the EKF Jacobians are computed for each soil layer to account for the soil water diffusion processes. Therefore computed soil moisture increments for each grid point of the model follow a vertical profile that results from a physically-based estimate of the relationship between the soil moisture profile and the parameters in the lower atmospheric level.

EKF Soil Moisture Analysis implementation

Although the OI system is limited in terms of both performances and flexibility in its use of different types of data, the OI system has 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 (125 km) to 20 seconds in CPU at T799 (25 km).

The EKF surface analysis is far more expensive than the OI system. At T159 its time consumption is close to 3×10^3 seconds in CPU. At T255 it increases to 10^4 CPU seconds and it is close to 2×10^5 CPU seconds at T799, for which is represents about one fifth of the 4D-Var time consumption. It was implemented to be used at T1279 in operations where it uses the same number of processors and threads as the upper-air analysis, leading to an elapsed time of 750 seconds (7×10^5 CPU seconds).

In order to enable the implementation of the EKF soil moisture analysis, the surface analysis structure was first revised in IFS cycle 35r3. In previous cycles the surface analysis was performed after the upper-air analysis. The surface analysis got 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 and there were some dependencies between the 4D-Var and the surface analysis. As a consequence the surface analysis was performed in the time critical path.

A new structure of the surface analysis was implemented with IFS cycle 35r3 in September 2009, with the surface analysis now being independent of the upper-air analysis. The observational dependency was resolved by creating a new observation data base dedicated to surface analysis. Consequently the field dependency issue mentioned above is resolved by using the first-guess fields instead of the upper-air analysis output fields. This means that the new surface analysis and the upper-air analysis are separated, so, they can be run in parallel. So, the surface analysis is not in the critical path anymore, thereby opening up the possibility of using a more sophisticated surface analysis scheme.

The new surface analysis structure 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 enabled the implementation of the EKF soil moisture analysis in IFS cycle 36r4 in November 2010.

Tests of the EKF soil moisture analysis

Experimental set up

In preparation for implementing the EKF soil moisture analysis three analysis experiments were conducted at T255 resolution over a one-year period (December 2008 to 30 November 2009).

- ***'OI' experiment***. The OI soil moisture analysis uses the increments of the screen-level parameters analysis as input. It represents the operational soil moisture analysis configuration that was used in operations at ECMWF from July 1999 to November 2010.
- ***'EKF' experiment***. This uses the dynamical EKF soil moisture analysis, in which the analysis of screen-level parameters is used as proxy information for soil moisture.
- ***'EKF+ASCAT' experiment***. This was conducted for the same one-year period using the EKF in which the analysis of screen-level parameters is used together with the ASCAT soil moisture data.

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). A first demonstration of the impact of using a nudging scheme 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. They recommended using ASCAT data in an EKF analysis to account for observation errors and to combine ASCAT data with screen-level proxy information. This is investigated in the 'EKF+ASCAT' experiment.

Note that:

- The 'OI' and 'EKF' experiments only differ in the method used for the soil moisture analysis. Observations used for the analysis are identical.
- The 'EKF' and 'EKF+ASCAT' experiments use the same EKF scheme, but satellite data is used in addition to conventional data in the 'EKF+ASCAT' experiment.

One month of spin-up is considered for the first month of the experiment, so results presented here focus on the period January to November 2009.

doi:10.21957/ik7co53s

Comparing the 'OI' and 'EKF' experiments

Figure 1 shows monthly accumulated soil moisture increments for the first metre of soil for July 2009 for the OI and EKF experiments, and their difference . Spatial patterns of soil moisture increments are quite similar for the OI and EKF schemes. For both the OI and the EKF the soil moisture increments are generally positive in most areas. However, negative increments are found in Argentina, Alaska and North East of America. These results mainly show that the EKF soil moisture analysis generally reduces the soil moisture analysis increments compared to the OI scheme.

Figure 2 shows the annual cycle of the global mean soil moisture increments for the OI and EKF experiments. It can be seen that the soil moisture increments of the OI scheme systematically add water to the soil. The global monthly mean value of the OI analysis increments is 5.5 mm, which represents a substantial and unrealistic contribution to the global water cycle. In contrast the EKF global mean soil moisture analysis increments are much smaller, representing global monthly mean increments of 0.5 mm. The reduction of increments between the EKF and the OI is mainly due to the reduction in increments below the first layer. 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 EKF dynamical estimates, based on perturbed simulations, allow the optimizing 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 EKF accounts for additional controls due to meteorological forcing and soil moisture conditions. Thereby it prevents undesirable and excessive soil moisture corrections.

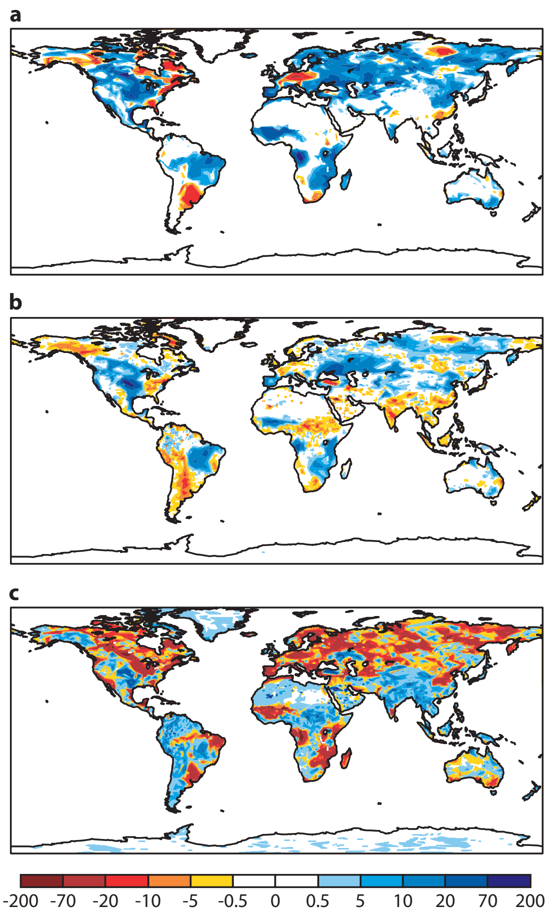


Figure 1 Monthly soil moisture increments (mm) within the top soil metre root zone (in mm) during July 2009 produced by (a) OI scheme and (b) EKF scheme. (c) Difference between EKF and OI schemes.

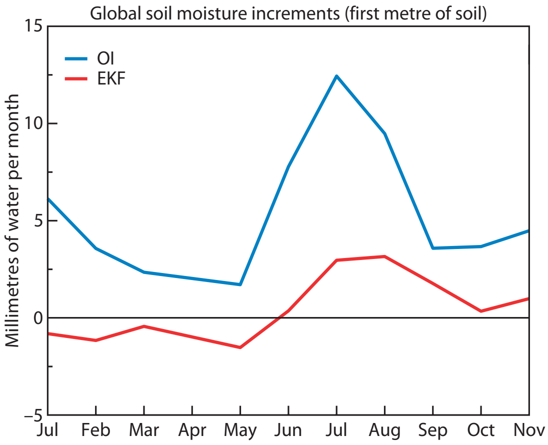


Figure 2 Temporal evolution of soil moisture increments in the first metre of soil (global mean value) in mm of water per month from January to November 2009, produced by the OI and EKF schemes.

Comparing 'OI', 'EKF' and EKF+ASCAT' experiments

Figure 3 shows the impact of the soil moisture analysis scheme on analysed soil moisture of the first soil layer (0–7cm) for all three experiments. Evaluation is conducted for 2009 against the 12 SMOSMANIA ground stations of the operational soil moisture network of Météo-France (*Calvet et al.*, 2007). It shows that ECMWF soil moisture is generally in good agreement with ground observations, with mean correlations higher than 0.78.

Using the EKF instead of the OI scheme 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 EKF and EKF+ASCAT). The bias and root-mean-square error are also improved with the EKF compared to the OI scheme. One may note that a strong negative bias is indicated for all schemes for one station, indicating that the analysis overestimates soil moisture content. This systematic difference in terms of volumetric soil moisture content is related to soil texture issues in this area for which the local ground data is not representative of the ECMWF model soil texture.

Results obtained from the EKF+ASCAT experiment show that using ASCAT does not improve the performance of the soil moisture analysis. In the experiment where ASCAT data is assimilated, soil moisture data has been re-scaled to the model soil moisture using a CDF matching, 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 Figure 3, 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. Test conducted with the new product prototype (not shown) considerably improved the usage of the ASCAT soil moisture data. Future experiments using an improved CDF-matching, with H-TESSEL corrected from precipitation errors, and improved data quality are expected to improve the impact of using ASCAT soil moisture in the data assimilation.

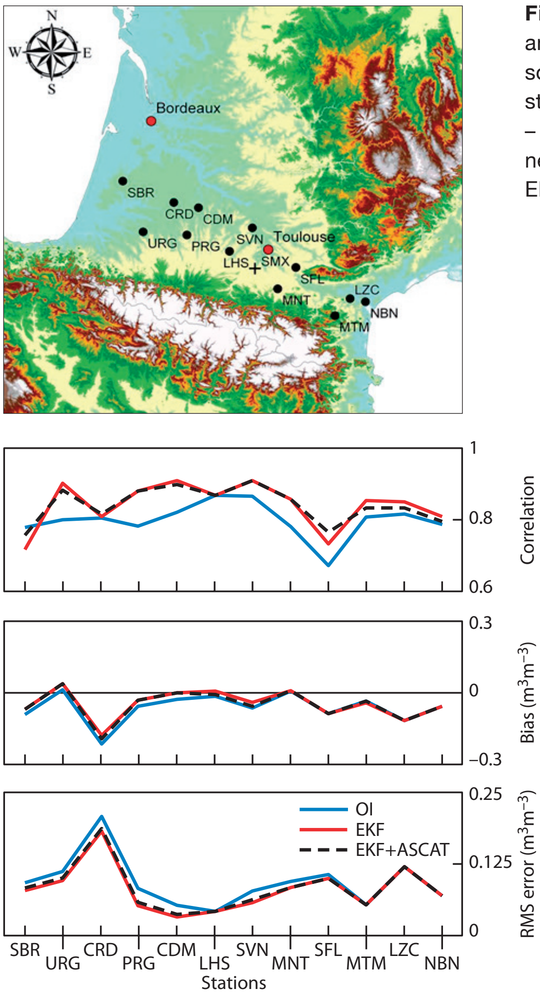


Figure 3 Correlation, bias (observation minus model) and root-mean-square (RMS) error of ECMWF surface soil moisture analysis of layer 1 for the 12 soil moisture stations in the SMOSMANIA (soil moisture observing system – meteorological automatic network integrated application) network in Southwest France in 2009, for the OI, EKF and EFF+ASCAT configurations of the soil moisture analysis.

doi:10.21957/ik7co53s

Impact on first guess and forecasts

Figure 4 shows the global impact of the EKF on the 2-metre temperature first guess that enters the analysis. The EKF soil moisture analysis scheme slightly improves the 2-metre temperature scores by consistently reducing the bias of the first-guess.

Figure 5 is an evaluation of the 48-hour forecast of 2-metre temperature (at 0000 UTC) for the African continent. It shows that the EKF reduces the night time cold bias compared to the OI scheme. Also the specific humidity (not shown) generally indicates drier conditions with the EKF than the OI scheme. Note that the ASCAT soil moisture data does not impact on screen-level variables and it has only a slight impact on soil moisture analysis as shown in Figure 3.

Figure 6 shows the monthly mean impact of the EKF soil moisture analysis on the 48-hour forecast of 2-metre temperature at 0000 UTC for July 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 for OI are larger than the EKF errors, showing that the EKF soil moisture analysis has a positive impact on the 2-metre temperature forecast.

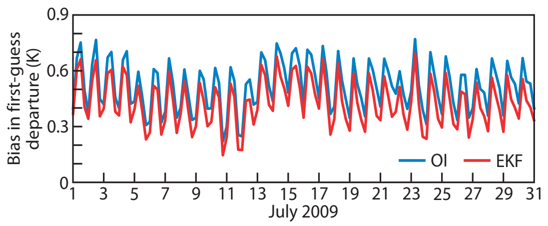


Figure 4 Temporal evolution of the bias in the first-guess departure (global mean) of the 2-metre temperature in July 2009 obtained wih the OI and EKF soil moisture analyses.

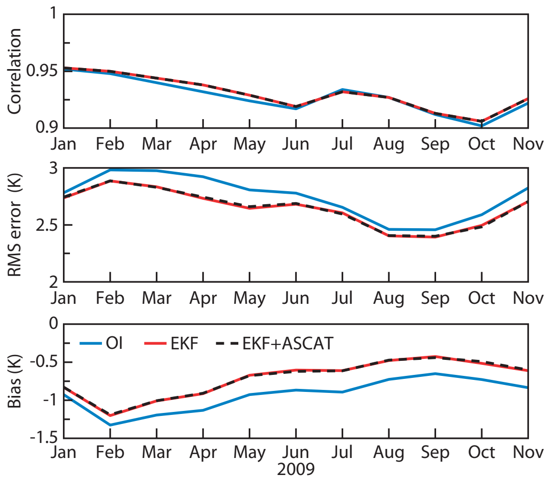


Figure 5 Correlation, root-mean-square (RMS) error and bias of 2-metre temperatures against SYNOP data in Africa from January 2009 to November 2009 for the OI and EKF schemes as implemented in operations (i.e. using conventional data of screen-level temperature and humidity), and the EKF when conventional data is combined with satellite soil moisture data from ASCAT.

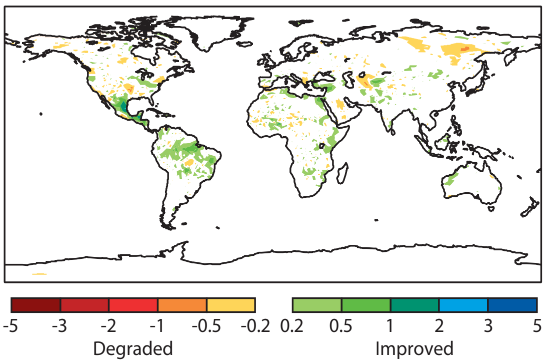


Figure 6 Monthly mean difference for July 2009 between the errors in the 36-hour forecasts (12 UTC) of 2-metre temperature for the OI and the EKF soil moisture analysis schemes. The forecasts are verified against the operational analysis.

doi:10.21957/ik7co53s

Summary and future developments

An Extended Kalman Filter (EKF) soil moisture analysis was implemented in operations with IFS cycle 36r4 in November 2010. Compared to the previous OI scheme, the EKF is a dynamical scheme that accounts for non-linear control on the soil moisture increments (meteorological forcing and soil moisture conditions). 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, 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 EKF soil moisture analysis enables the combined use of screen-level parameters and satellite data, such as ASCAT soil moisture data, to analyse soil moisture. Results with ASCAT data assimilation show a neutral impact on both soil moisture and screen-level parameters. However improvements in the ASCAT soil moisture products and in bias correction are expected to improve the impact of using ASCAT soil moisture data.

The new EKF soil moisture analysis system opens a wide range of further development possibilities, including exploiting new satellite surface data and products for the assimilation of soil moisture. An extension of the EKF to analyse additional variables, such as snow mass and vegetation parameters, is planned for investigation in the near future.

Further reading

Calvet, **J.-C.**, **N. Fritz**, **F. Froissard**, **D. Suquia**, **A. Petitpa** & **B. Piguet**, 2007: In situ soil moisture observations for the CAL/VAL of SMOS: the SMOSMANIA network. *International Geoscience and Remote Sensing Symposium*, IGARSS, Barcelona, Spain, doi: 10.1109/IGARSS.2007.4423019, 2007.

de Rosnay, **P.**, **M. Drusch**, **G. Balsamo**, **A. Beljaars**, **L. Isaksen**, **D. Vasiljevic**, **C. Albergel** & **K. Scipal**, 2009: Advances in land data assimilation at ECMWF. In *Proc. ECMWF/GLASS Workshop on Land Surface*, Reading, UK, 9–12 November 2009, http://www.ecmwf.int/publications/library/do/references/show?id=89853

Drusch, **M.**, **K. Scipal**, **P. de Rosnay**, **G. Balsamo**, **E. Andersson**, **P. Bougeault** & **P. Viterbo**, 2008: Exploitation of satellite data in the surface analysis. *ECMWF Tech. Memo. No. 576*, http://www.ecmwf.int/publications/library/do/references/show?id=88712

Mahfouf, **J.-F.**, 2000: A revised land-surface analysis scheme in the Intergrated Forecasting System. *ECMWF Newsletter No. 88*, 8–13, http://www.ecmwf.int/publications/newsletters/pdf/88.pdf

Scipal, **K.**, **M. Drusch** & **W. Wagner**, 2008: Assimilation of a ERS scatterometer derived soil moisture index in the ECMWF numerical weather prediction system. *Adv. Water Res*., doi:10.1016/j.advwatres.2008.04013.

 doi:10.21957/ik7co53s