# Land surface data assimilation

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## 1 Introduction

Land surface processes determine the lower boundary conditions of the atmosphere and they represent a crucial component of the hydrological cycle (Entekhabi et al., 1999; Koster and Suarez, 1992; Sukla and Mintz, 1982). In Numerical Weather Prediction (NWP) and climate models, surface-atmosphere interaction processes are represented by Land Surface Models (LSMs). These models have been improved considerably during the last two decades and nowadays they model exchanges of water and energy through the soil-plant-atmosphere continuum with a good consistency between land surface fluxes and soil moisture (e.g. Balsamo et al., 2009; Krinner et al., 2005; de Rosnay et al., 2002). Land surface initialisation is of crucial importance for NWP. Soil moisture determines the partitioning of energy between latent and sensible heat fluxes. A number of studies have shown a significant impact of soil moisture on weather forecast skill at short and medium range (van den Hurk et al., 2008; Drusch and Viterbo, 2007; Douville et al., 2000; Mahfouf et al., 2000; Beljaars et al., 1996) as well as at seasonal range (Weisheimer et al., 2011; Koster et al., 2011, 2004). Cold processes are also a key component of the land-surface interactions. Snow is characterised by a very high albedo, a low thermal conductivity and it represents a significant surface water storage reservoir (Brown and Mote, 2009; Barnett et al., 2005). Snow has therefore a strong influence on the summer water supply and it affects the energy balance at the surface and the surface atmosphere interactions (Gong et al., 2004; Walland and Simmonds, 1997). Initialisation of snow conditions also has a large impact on the forecast accuracy as show by Drusch et al. (2004) and Brasnett (1999).

In this paper, methods used to analyse LSMs prognostic variables in operational NWP models are reviewed. The ECMWF recent developments in both the soil moisture analysis and the snow analysis are used to illustrate the different approaches used in the NWP community. Section 2 addresses snow analysis. Current ground and satellite observations available are presented, and methods used to analyse snow depth in NWP systems are described and compared. Section 3 reviews soil moisture analysis systems used for NWP applications. Use of satellite data to analyse soil moisture is discussed in Section 5. Finally, section 6 concludes the paper.

## 2 Snow Analysis

### 2.1 Snow forecast model

LSMs describe snow on the ground using several prognostic variables, including the Snow Water Equivalent ($SWE$) in $m$, and the snow density $\rho_s^b$ ($kgm^{-3}$). Accounting for liquid water density ($\rho_s^b$ equal 1000 $kgm^{-3}$) and snow density, snow depth $S^b$ ($m$), is expressed as: $S^{\mathrm{b}} = (\rho_w \times SWE_s^b)/\rho_s^b$. Snow processes are parameterized in LSMs to account for snow accumulation on the ground, snow melting, snow compaction, etc.... At ECMWF, H-TESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchange over Land, described in Balsamo et al., 2009; Viterbo and Beljaars, 1995) is used to represent the surface processes (also see the ECMWF Integrated Forecasting System, IFS, documentation: ECMWF, 2012). A new snow parameterisation was implemented operationally in H-TESSEL in 2009 to account for liquid water content in the snowpack and to improve the diagnostic of Snow Cover Fraction by considering both SWE and snow density (Dutra et al., 2010). It allows representing hysteresis in snow cover fraction between accumulation and depletion periods. In addition it includes a new snow density parameterisation of fresh snow that accounts for wind speed and air temperature effect on snow density. Snow models allow to represent the evolution of the snowpack in NWP models. However, accurate initialisation of snow variables, by optimally combining model first guess and observations in data assimilation schemes, is required to give a reliable description of the snowpack evolution.

### 2.2 Snow observations

Snow analysis systems strongly rely on ground observations of snow depth (Drusch et al., 2004; Brasnett, 1999). SYNOP (synoptic reports) snow depth observations are available in Near Real Time (NRT) on the Global Telecommunication System (GTS). In addition to SYNOP reports, most weather services also have national snow depth measurements networks. In the USA, the SNOTEL (SNOwpack TELemetry) network provides snow depth measurements used in the NOAA (National Oceanic and Atmospheric Administration) National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC) SNOw Data Assimilation System (SNODAS), however these data sets are not available on the GTS and therefore they are not used in NWP snow analysis systems. Over Europe, several countries are currently making available their snow depth measurements to the NWP community. These data have been assimilated at ECMWF since March 2011 (de Rosnay et al., 2011a). Ground measurements are accurate, however they are very local. So, they are affected by representativeness errors and many areas are not observed (e.g. large areas in Siberia).

In contrast, satellite observations provide spatially integrated measurements with global coverage. They have been foreseen to be of great potential interest to provide consistent snow information for climate and NWP communities. For example, SWE products based on passive microwave measurements from AMSR-E (Advanced Microwave Scanning Radiometer for Earth Observing System) is available. However retrieval algorithms are sensitive to many parameters such as snow grain size distribution, snow liquid water content, which are very difficult to estimate. Therefore current SWE satellite products still have a limited accuracy, particularly for deep snow conditions. Future sensors such as the ESA (European Space Agency) Earth Explorer CoReH2O mission are designed to accurately retrieve SWE, using dual polarisation measurements at frequencies optimal to separate grain size and SWE effect on the microwave emission Rott et al. (2009). It is also possible to access the Snow Cover Fraction (SCF) information with a good accuracy from Visible and Near infrared measurements, but a limitation of these measurements is that they require cloud free conditions. The NOAA/NESDIS (National Environmental Satellite, Data, and Information Service) Interactive Multi-sensor Snow and Ice Mapping System (IMS) combines ground observations, microwave and visible measurements to provide snow cover information in all weather conditions. The IMS product is available daily for the northern hemisphere (Helfrich, 2007; Brubaker et al., 2005; Ramsay, 1998). The NOAA/NESDIS/IMS snow cover product is available at 24km resolution or a 4km (Helfrich, 2007). At ECMWF the 24 km NESDIS/IMS snow cover product was used to analysis snow in operations from 2004 to 2010 (Drusch et al., 2004). Since 2010 the 4km product has been used (de Rosnay et al., 2011b).

### 2.3 Snow Analysis methods

Snow analysis schemes used in operational NWP systems rely on simple methods. At the DWD (Deutscher Wetterdienst) a Cressman Interpolation is used (Cressman, 1959). A Cressman analysis was also used in operations at ECMWF for more than 20 years until it was replaced by a 2 dimensional (2D) Optimum Interpolation in November 2010 de Rosnay et al. (2011b). The ECMWF Re-Analysis ERA-Interim still uses the Cressman interpolation (Dee et al., 2011). The Canadian Meteorological Center (CMC) uses an Optimum Interpolation (OI) scheme developed by Brasnett (1999) to account for vertical and horizontal structure functions.

The ECMWF snow analysis is a two-step algorithm. In the first step, the background snow depth field $S^{\mathrm{b}}$ (as defined above) is compared with the NOAA/NESDIS snow extent product (Drusch et al., 2004). Grid boxes, which have a snow depth lower than 0.01 $m$ in the first guess but are snow covered in the satellite derived product, are updated with a constant snow depth of 0.1 $m$ of density 100 $kgm^{-2}$. In the second step, the Optimum Interpolation is run using $N$ observations from ground stations reports and snow free satellite observations (which enter the analysis with a snow depth equal to 0 m). The snow depth analysis increment is computed at each model grid point $p$:

$$\Delta S_p^{\mathrm{a}} = \sum_{i=1}^{N} W_i \times \Delta S_i \tag{1}$$

where $\Delta S_i$ is the background increment at each observation location $i$ and $W_i$ are corresponding optimum weights. The difference between the OI and Cressman lies in the computation of the weighting functions.

### 2.3.1 Cressman Interpolation

Following Cressman (1959), the weighting functions used in Equation 1 are computed at each observation location:

$$W_i = \frac{w_i}{\sum_{i=1}^{N} w_i} \tag{2}$$

with $w_i$ the product of functions of the horizontal distance $r$ and vertical displacement $h$ between the observation and analysis points:

$$w = H(r)v(h) \tag{3}$$

where the horizontal function is:

$$H(r) = \max\left(\frac{r_{\max}^2 - r^2}{r_{\max}^2 + r^2}, 0\right) \tag{4}$$

and the vertical function is:

$$v(h) = 1 \quad \text{if } 0 < h$$
$$v(h) = \frac{h_{\max}^2 - h^2}{h_{\max}^2 + h^2} \quad \text{if } -h_{\max} < h < 0$$
$$v(h) = 0 \quad \text{if } h < -h_{\max}$$

For the Cressman interpolation used at ECMWF, the influence distances are set to $r_{\max} = 250$ km and $h_{\max} = 300$ m. The observation height of the ground data is provided together with the snow depth data in the SYNOP report, whereas for the satellite data it is obtained at the pre-processing step from the model orography field. Observations and background errors are not taken into account in the weighting functions.

The snow depth is preserved when the model height is above the observing station, but it is severely reduced below. The horizontal structure function is shown in Figure 1. It is characterised by a sharp drop at 250 km.

### 2.3.2 Optimum Interpolation

Following the Optimum Interpolation theory, the weighting functions of Equation 1 are given in matrix form by:

$$(\mathbf{B}+\mathbf{O})\mathbf{W}=\mathbf{b} \tag{5}$$

The column vector $\mathbf{b}$ (dimension $N$) represents the background error covariance between the observation $i$ and the model grid-point $p$. $\mathbf{W}$ is the column vector of weights at each observation location. The $(N\times N)$ matrix $\mathbf{B}$ describes the error covariances of background fields between pairs of observations $(i,j)$ and $\mathbf{O}$ is the covariance matrix of the observations errors.
For the snow analysis the horizontal correlation coefficients (structure functions) of $\mathbf{b}$ and $\mathbf{B}$ follow the formulation proposed by Brasnett (1999):

$$\mu_{ij}=\alpha(r_{ij})\beta(\Delta z_{ij}) \tag{6}$$

where $r_{ij}$ and $z_{ij}$ are the horizontal and the vertical separation between points $i$ and $j$, respectively. $\alpha(r_{ij})$ and $\beta(\Delta z_{ij})$ are the horizontal and vertical structure functions respectively:

$$\alpha(r_{ij})=(1+\frac{r_{ij}}{L})\exp(-\frac{r_{ij}}{L}) \tag{7}$$

$L$ is the horizontal length parameter taken to 55 $km$, corresponding to an e-folding distance of 120 km.

$$\beta(\Delta z_{ij})=\exp\left(-\left[\frac{\Delta z_{ij}}{h}\right]^2\right) \tag{8}$$

$h$ is the vertical length scale taken to 800 m. The horizontal structure functions used in the snow analysis based on Cressman and the OI are shown in Figure 1. The OI has longer tails than the Cressman interpolation. It accounts for observations and background errors in the interpolation procedure, allowing a better use of the data.

## 2.4 Results

The 2009/2010 winter season, with cold and snowy conditions in the northern hemisphere, highlighted the importance of good quality snow analysis. Snow can have significant impact on temperature forecasts, directly affecting the accuracy of forecasts communicated to customers and forecast users. Furthermore, the snow mass influences the evolution of soil moisture for up to several months as a water reservoir that is released by snow melt. The new snow analysis was implemented at ECMWF in November 2010. It uses the Optimum Interpolation (OI) surface analysis scheme, which has been used for 2 metre temperature and 2 meter humidity for many years Mahfouf et al. (2000). The specification of structure functions for the OI snow analysis closely follows the implementation of Brasnett (1999) at the Canadian Meteorological Centre, as described in the previous section. In addition, routine acquisition of the NESDIS higher-resolution (4 km) snow cover product has begun and this data has been used instead of the 24 km product in the new snow analysis since November 2010. The 4 km NESDIS product provides better snow cover definition than the 24 km product, especially in coastal areas. For SYNOP reports, snow depth data quality control and a station blacklist have been introduced. Detailed information concerning SYNOP data rejections is being generated and stored for subsequent inspection.
Figure 2 shows the influence of the new snow analysis on the snow depth pattern in north-east Asia. The Cressman analysis produces disk-shaped spurious patterns of snow in northern Asia related to the Cressman interpolation. The Optimum Interpolation analysis makes a better use of SYNOP snow depth data than Cressman. It presents a smoother and more correct snow analysis without spurious patterns. Three month analysis experiments were conducted to evaluate the impact of the new analysis with separate contributions from the OI and the 4km NESDIS/IMS product. The new snow analysis has an

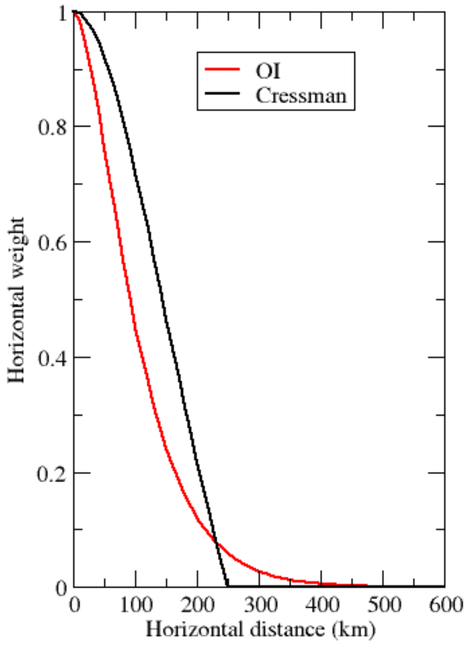


*Figure 1: Horizontal structure functions used at ECMWF in the Cressman Interpolation (used in operations from 1987 to 2010) and in the Optimum Interpolation scheme (used since November 2010) for the snow depth analysis.*

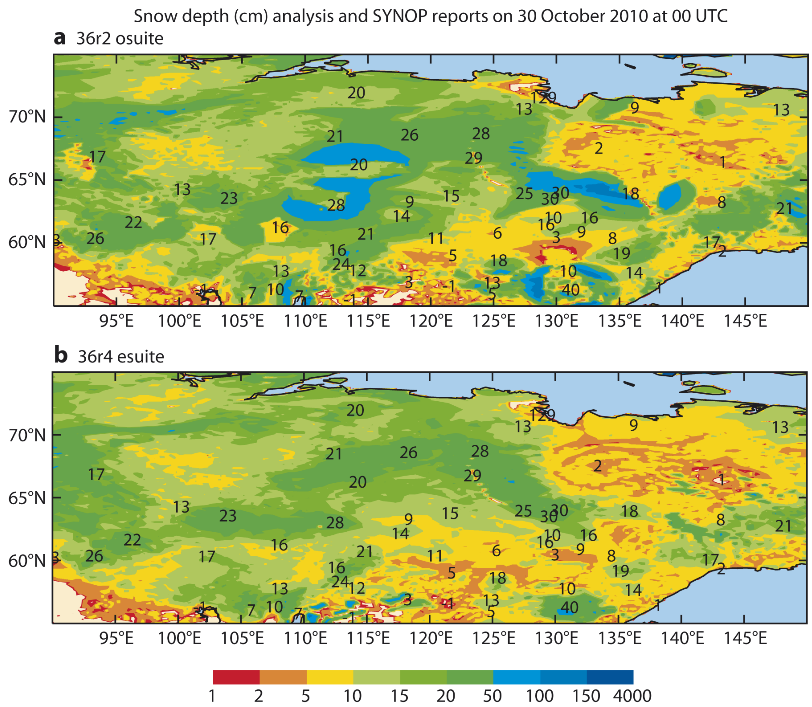


*Figure 2: Comparison of snow depth analysis between operational suite using Cressman snow analysis (top) and the test suite using the OI snow analysis (bottom) in northern Asia on 30 October 2010. SYNOP snow depth measurements are reported in black on the figure.*

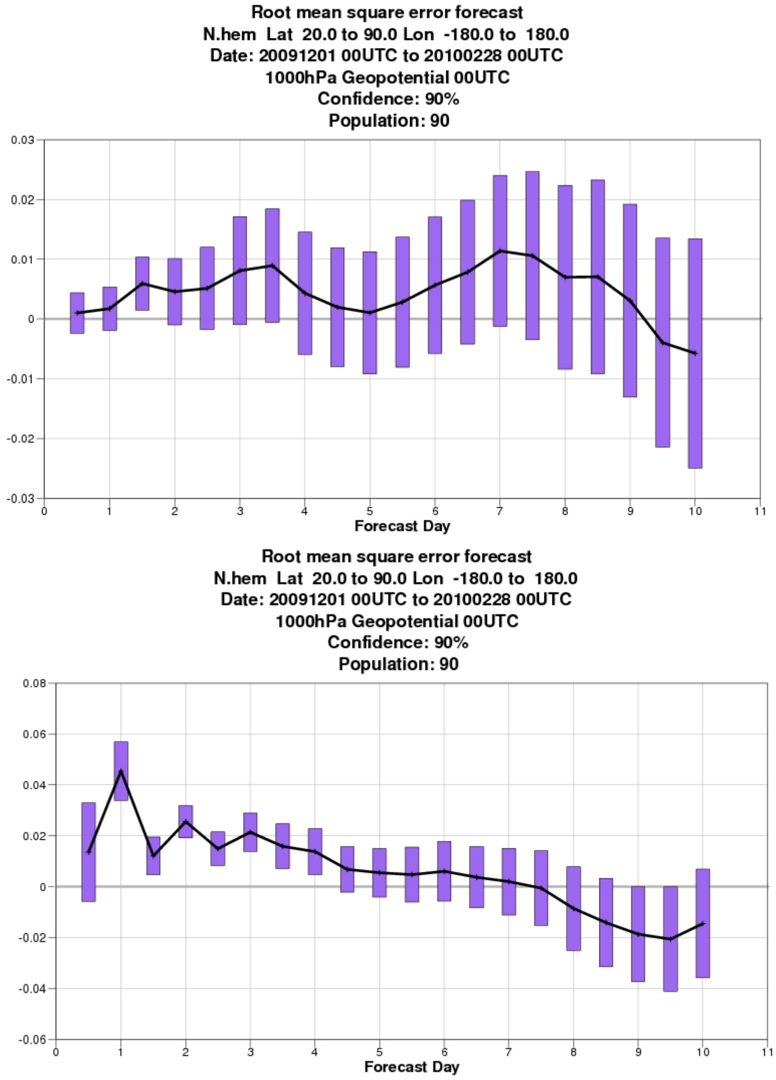


*Figure 3: Impact of the new snow analysis on the 1000 hPa geopotential height forecast, for the OI component only (OI analysis with the 24 km NOAA/NESDIS/IMS product) and the new analysis scheme (OI analysis with improved use of NOAA/NESDIS/IMS data) on the bottom. The y-axis represents the difference in root mean square error between the old analysis and the new analysis. So positive impact is shown by positive value.*

overall positive impact on the atmospheric forecasts skill. Improved use of the NESDIS/IMS product has a clear positive impact on the forecast performance, which is significantly improved in the northern hemisphere, during the first 4 days of forecast range for the 1000 hPa geopotential height field (Figure 3 bottom).

# 3 Soil Moisture analysis

## 3.1 History of soil moisture analysis at ECMWF

As shown by Mahfouf (1991), near surface meteorological observations of 2 metre temperature and relative humidity, which are measured routinely by the SYNOP operational network, can be used to infer realistic soil moisture estimates.

The first soil moisture analysis system used for operational NWP was implemented by 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, a 1-dimensional (1D) Optimum Interpolation soil moisture analysis was implemented operationally at ECMWF to replace the nudging scheme (Douville et al., 2000; Mahfouf et al., 2000). The OI soil moisture analysis relies on the fact that soil wetness errors are negatively and positively correlated with 2 metre temperature and relative humidity errors, respectively. 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 1D 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 by finite differences based on perturbed simulations. Based on this approach Météo-France developed an offline simplified EKF soil analysis scheme within 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 on the low level atmospheric parameters. 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 analyses soil moisture, 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 an 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 soil moisture analysis (Seuffert et al., 2004). Based on local scale analysis experiments (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.
A simplified EKF soil moisture analysis was developed at ECMWF and implemented in the IFS (de Rosnay et al. (2012, 2011c); Drusch et al. (2009)). In the following section differences between EKF and OI soil moisture analyses are presented in terms of soil moisture and low level atmospheric parameters.

## 4 Comparison between the OI and EKF soil moisture analyses

Figure 4 shows the annual cycle of the global mean soil moisture increments for the OI and EKF experiments. It shows 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 more reasonable global monthly mean increments of 0.5 mm. The reduction of increments between the EKF and the OI is mainly due to the reduction of 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 the OI increments. In contrast the EKF dynamical estimates, based on perturbed simulations, allow optimising 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 (de Rosnay et al., 2012).

The impact of the soil moisture analysis scheme on analysed soil moisture was also studied using ground data from SMOSMANIA (Soil Moisture Observing System - Meteorological Automatic Network Integrated Application, see Albergel et al., 2008; 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), as shown in de Rosnay et al. (2011c).

Figure 5 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.

## 5 Use of satellite data to analyse soil moisture

In the past few years several new space-borne microwave sensors have been developed to estimate soil moisture from space. 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 (Bartalis et al., 2007). 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 (`http://www.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/slmoist/ascat/`). Scipal et al. (2008) investigated the impact of scatterometer soil moisture products (from the European Remote-Sensing ERS) data assimilation in a simple nudging scheme. They showed that, compared to the model "open-loop" (without data

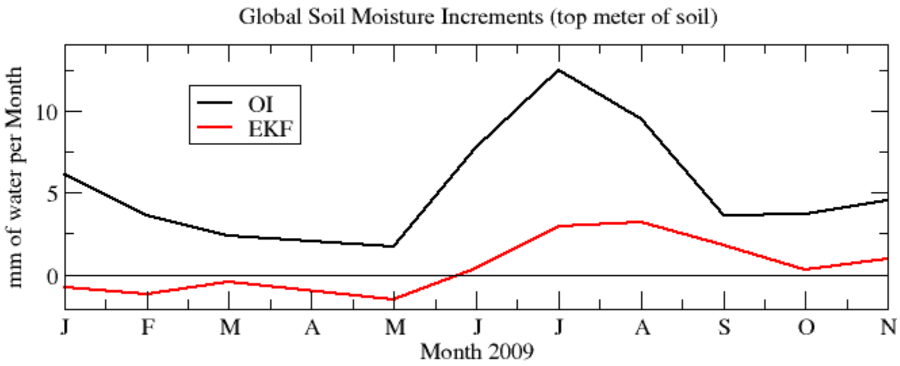


*Figure 4: Soil water increments (mm per month) in the first metre of soil (global mean value) for the period January to November 2009, with the OI and EKF analyses.*

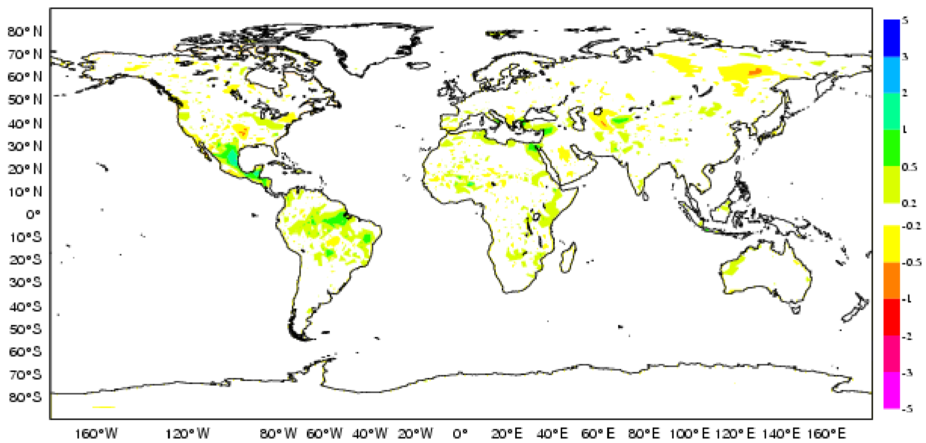


*Figure 5: Difference of July monthly mean 48 hour forecasts (12 UTC) error in 2 metre temperature between the OI and the EKF soil moisture analysis schemes.*

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. de Rosnay et al. (2012) investigated the use of ASCAT soil moisture data in the EKF soil moisture analysis, showing a neutral impact on both soil moisture and screen level parameters forecasts. 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 analyses soil moisture from screen level parameter 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.

The ESA SMOS (Soil Moisture and Ocean Salinity) mission was launched in 2009 (Kerr et al., 2010). Based on L-band passive microwave measurements, SMOS is the first mission dedicated to soil moisture remote sensing. The future NASA SMAP (Soil Moisture Active and Passive) mission, planned 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 (Entekhabi et al., 2010). ECMWF plays a major role in developing and investigating the use of new satellite data for soil moisture analysis. SMOS brightness temperature product has been monitored in near-real time since November 2010, as described in Sabater et al. (2011). It is available at: `http://www.ecmwf.int/products/forecasts/d/charts/monitoring/satellite/smos/`. Work toward assimilation of SMOS data is progressing well.

## 6 Conclusion

This paper discusses the current status of data assimilation systems used to initialise land surface variables for NWP. Based on ECMWF experience and recent developments, snow and soil moisture analysis methods and observations are discussed.

The current approaches used to analyse snow depth in NWP systems are reviewed. Snow analysis schemes rely on simple approaches such as Cressman Interpolation or Optimum Interpolation. At ECMWF the Cressman Interpolation was replaced by an OI in 2010, following the approach already used at CMC since 1999. It is shown that the OI allows a better use of the observations than Cressman interpolation. In addition the use of satellite snow cover information was revised at ECMWF by using the high resolution (4km) IMS product, with a revised pre-processing. The new snow analysis is shown to have an overall positive impact on the atmospheric forecasts. Currently snow depth analysis systems use observations from ground networks (SYNOP and national data) and snow cover information from NOAA/NESDIS IMS. Other satellite products provide SWE, but are not used for NWP applications. Future missions such as the ESA CoReH2O mission are expected to provide SWE information from space with an improved accuracy compared to current SWE products.

Concerning soil moisture most NWP centres use a 1D OI analysis to initialise soil moisture based on a dedicated screen level parameters analysis. At DWD and at ECMWF an EKF soil moisture analysis is used in operations. The EKF soil moisture analysis is also based on a dedicated screen level parameters analysis. Whereas the OI uses screen level analysis increments as input of the soil moisture analysis, the EKF uses analysed screen level fields as input observations of the soil moisture analysis. The EKF soil moisture analysis is shown to reduce the soil moisture increments compared to the OI, and it improves both soil moisture and screen level parameters analyses and forecasts. In addition the EKF makes it possible to combine screen-level parameters and satellite data, such as ASCAT or SMOS, to analyse soil moisture. Results with ASCAT data assimilation showed a neutral impact on both soil moisture and screen-level parameters. However recent 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 (e.g. SMOS, or the future SMAP) 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.

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