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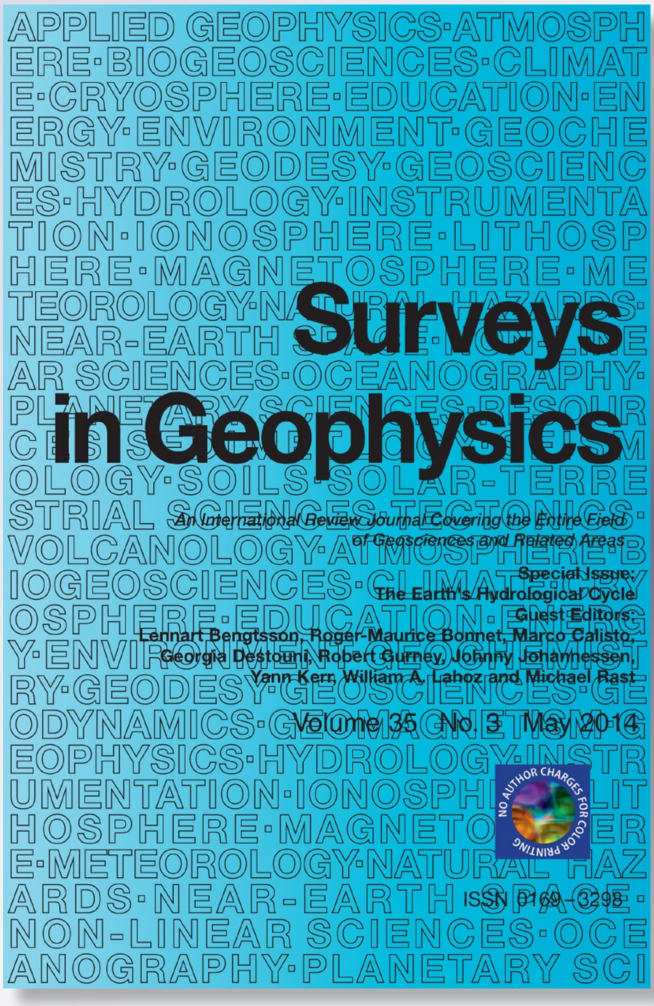

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Initialisation of Land Surface Variables for Numerical Weather Prediction

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Abstract Land surface processes and their initialisation are of crucial importance for Numerical Weather Prediction (NWP). Current land data assimilation systems used to initialise NWP models include snow depth analysis, soil moisture analysis, soil temperature and snow temperature analysis. This paper gives a review of different approaches used in NWP to initialise land surface variables. It discusses the observation availability and quality, and it addresses the combined use of conventional observations and satellite data. Based on results from the European Centre for Medium-Range Weather Forecasts (ECMWF), results from different soil moisture and snow depth data assimilation schemes are shown. Both surface fields and low-level atmospheric variables are highly sensitive to the soil moisture and snow initialisation methods. Recent developments of ECMWF in soil moisture and snow data assimilation improved surface and atmospheric forecast performance.

Keywords Land surface · Data assimilation · Numerical weather prediction · Soil moisture · Snow

1 Introduction

Land surface processes determine the lower boundary conditions of the atmosphere, and they represent a crucial component of the hydrological cycle (Mueller and Seneviratne 2012; Entekhabi et al 1999; Koster and Suarez 1992; Shukla 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 represent exchanges of water and energy through the soil–plant–atmosphere continuum with a good

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P. de Rosnay (✉) · G. Balsamo · C. Albergel · J. Muñoz-Sabater · L. Isaksen
European Centre for Medium-Range Weather Forecasts, Reading, Berkshire, UK
e-mail: Patricia.Rosnay@ecmwf.int

consistency between land surface fluxes and soil moisture (Best et al. 2011; Balsamo et al. 2009; Krinner et al. 2005; de Rosnay et al. 2002).

Land surface initialisation is of crucial importance for NWP. A number of studies have shown a significant impact of soil moisture conditions 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 and a low thermal conductivity, and the snowpack constitutes a substantial water storage reservoir (De Lannoy et al. 2012; Brown and Mote 2009; Barnett et al. 2005). Snow has 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). So, initialisation of snow conditions has a large impact on the atmospheric forecast accuracy (Drusch et al 2004; Brasnett 1999).

In this paper, methods used in operational NWP models to analyse LSMs' prognostic variables are reviewed. Section 2 describes current snow analysis approaches used in NWP centres. It presents ground and satellite observations of snow that are relevant to operational applications and shows results of snow data assimilation experiments. Based on results from the European Centre for Medium-Range Weather Forecasts (ECMWF), the impact on the atmospheric forecasts is presented and compared for different snow data assimilation approaches. Section 3 reviews soil moisture analysis systems used for NWP applications. It includes a discussion on the use of satellite data to analyse soil moisture. ECMWF results are shown to illustrate the influence of different soil moisture analysis approaches on surface and low-level atmospheric fields. Concluding remarks are given in Sect. 4.

2 Snow Analysis

2.1 Snow Forecast Models

Snow processes are parameterised in LSMs to account for a range of processes, including snow accumulation on the ground, snow melting and snow compaction. The LSM used at ECMWF is H-TESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchange over Land) (ECMWF 2012; Balsamo et al. 2009; Viterbo and Beljaars 1995). H-TESSEL snow parameterisation was revised in 2009 (Dutra et al. 2010). It now accounts for liquid water content in the snowpack, and it includes a new snow density formulation that expresses the fresh snow density as a function of wind speed and air temperature. Snow Cover Fraction (SCF) and Snow Water Equivalent (SWE) are related by a depletion curve which depends on snow density. So, H-TESSEL represents the SCF hysteresis between accumulation and depletion periods (Dutra et al. 2010).

H-TESSEL has an explicit treatment of the snowpack evolution, and it uses a single-layer snow model, in contrast to LSMs used at the United Kingdom Meteorological Office (UKMO) or at Météo France, which include a multi-layered snow scheme (Best et al. 2011; Dutra et al. 2010; Boone et al. 2004). Like most other LSMs, H-TESSEL represents the effects of snow on the surface roughness length and for sub-grid scale processes. Current LSMs represent well the duration of snow cover; however, they still have large uncertainties in terms of snow accumulation, due to inaccuracies in the meteorological forcing and to imperfect model parameterisations (Essery et al. 2009; Boone et al. 2004). Data assimilation approaches, by optimally combining models and observations, are expected to provide most accurate estimates of snow conditions (Pullen et al. 2011; Essery et al. 2009; Drusch et al. 2004; Brasnett 1999).

2.2 Snow Observations

Snow data assimilation strongly relies on snow depth ground observations (Drusch et al. 2004; Brasnett 1999). A major source of snow depth measurements is that provided by SYNOP stations (synoptic reports). These observations are available in near-real time (NRT) on the Global Telecommunication System (GTS), so they are suitable for NWP applications. In addition to SYNOP reports, most weather services maintain national snow depth measurements networks. For example, 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). The NOAA COoperative Observer Program (COOP) also provides snow depth measurements over North America. However, data gathered from National Networks are not available on the GTS, and therefore, they are not suitable to be used in NWP snow analysis systems. In Europe, several countries are currently making available their snow depth measurements to the NWP community. The Swedish Meteorological and Hydrological Institute was the first to release its national network snow depth data on the GTS from December 2010. These data have been assimilated at ECMWF since March 2011 (de Rosnay et al. 2011a). Ground measurements of snow depth provide a very accurate local information, however, because of the variability of land surface and meteorological conditions, their representativeness can be limited, particularly in heterogeneous and in mountainous areas. Besides, many areas are sparsely observed (e.g., large areas in Siberia). Based on comparisons between pointwise SYNOP snow depth data and snow survey data sets, Takala et al. (2011) estimated the uncertainty of SYNOP snow depth data to be close to 0.12 m.

Satellite observations provide spatially integrated measurements with global coverage which makes them of high interest to provide consistent snow information for climate and NWP communities. SWE products based on passive microwave measurements, for example, from AMSR-E (Advanced Microwave Scanning Radiometer for Earth Observing System), product are available. However, retrieval algorithms are sensitive to many parameters such as snow grain size distribution and snow liquid water content, which are very difficult to estimate. Therefore, current satellite-based SWE products still have a limited accuracy, particularly for deep snow conditions (Takala et al. 2011). Future sensors, such as the proposed 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 effects on the microwave emission (Rott et al. 2009).

While there are still high uncertainties in SWE retrievals from space-borne sensors, it is possible to estimate the Snow Cover Fraction with a good accuracy from Visible and Near infrared measurements in cloud-free conditions (Brubaker et al. 2009). The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments provide high-resolution (0.05°) daily observations of snow cover. The MODIS snow cover product is used in the NASA (National Aeronautics and Space Administration)/NOAA Global Land Data Assimilation System (GLDAS, Rodell and Houser 2004). The NOAA/NESDIS (National Environmental Satellite, Data, and Information Service) Interactive Multi-sensor Snow and Ice Mapping System (IMS) combines ground observations and satellite data from microwave and visible sensors (using geostationary and polar orbiting satellites) to provide snow cover information in all weather conditions. It provides a binary information on snow cover. In other words, it indicates if there is snow or not on the ground, but if there is snow, it does not indicate the snow quantity on the ground. The IMS product is available daily for the northern hemisphere (Helfrich et al. 2007; Brubaker et al. 2009; Ramsay 1998). It is available from 1997 at a resolution of 24 km (Ramsay 1998) and from 2004 at 4 km resolution (Helfrich et al. 2007). The NOAA NESDIS IMS snow cover product has been used to analyse snow in NWP systems at ECMWF and the UKMO since 2004 and 2008, respectively (Pullen et al. 2011; de Rosnay et al. 2011b; Drusch et al. 2004). It is also used in the latest National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (Meng et al. 2012).

2.3 Snow Analysis Methods

A number of NWP centres recently developed snow analysis approaches to improve the initialisation of snow variables, with expected impacts on the near surface weather parameters.

The UKMO snow analysis was implemented in operations 2008. It entirely relies on the NOAA NESDIS IMS 4 km Snow Cover information (Pullen et al. 2011). As part of the IMS pre-processing, the 4-km product is interpolated on the Unified Model grid, and a snow cover fraction is computed for each model grid point. To correct the model snow depth prognostic variable, a simple update approach is used, as described by Pullen et al. (2011). If the IMS product indicates snow-free conditions, the analysed snow depth is set to zero. Otherwise, the IMS snow cover is compared to the model background. If IMS indicates a region is snow covered and the model background agrees, the model is simply cycled, that is, the analysed snow depth is set to the background snow depth. If IMS indicates a region is covered by snow while the model background is snow free, the analysed snow depth is computed as a function of the observed snow cover using a logarithmic depletion curve.

The NASA/NOAA GLDAS snow analysis follows a similar approach along the same line, using the MODIS snow cover product (Rodell and Houser 2004). The NCEP CFSR reanalysis also relies on a simple update approach, with input data resulting from combined IMS and Air Force Weather Agency's snow depth analysis (SNODEP), as described by Meng et al. (2012).

Most of other NWP services use SYNOP snow depth reports available on the GTS. The snow analysis is a spatial interpolation of weighted background and observed snow depth. The DWD (Deutscher Wetterdienst) assimilates SYNOP reports of snow depth using the Cressman (1959) interpolation. The Cressman analysis accounts for weighting functions of vertical and horizontal distances between observations and model grid points. The Canadian Meteorological Center (CMC) uses a 2D Optimal Interpolation (OI) scheme developed by Brasnett (1999). Similarly to the Cressman interpolation, the OI expresses the observations weighting functions from vertical and horizontal structure functions. In addition, it accounts for covariance matrices of background and observations errors which enable to optimally combine model background and observations. At ECMWF, the latest ECMWF Re-Analysis, ERA-Interim, uses a Cressman interpolation for the snow analysis (Dee et al. 2011). The operational snow analysis relied on a Cressman interpolation for more than 20 years until it was replaced by a 2D Optimal Interpolation in November 2010 (de Rosnay et al. 2011b). The ECMWF operational snow analysis is a two-step algorithm. In the first step, a simple update scheme similar to the one used at NCEP or at the UKMO is used to account for the IMS snow cover information. Grid boxes, which are snow free in the model background but are snow covered in the satellite-derived product, are updated with a constant snow depth of 0.1 m of density 100 kg m^{-2}. In the second step, observations from ground stations reports and snow-free satellite observations (which enter the analysis with a snow depth equal to 0 m) are assimilated using an OI to produce the analysed snow field.

As described above for CMC, DWD, ECMWF, NASA/NOAA and NCEP, NWP systems generally use simple data assimilation approaches to initialise snow depth, ranging from simple update, Cressman Interpolation and Optimal Interpolation.

2.4 Results

Figure 1 shows snow depth analysis fields in north-east Asia on 30 October 2010, obtained from the ECMWF Integrated Forecasting System when using a Cressman snow analysis (top) and an OI snow analysis (bottom). A qualitative comparison shows that the Cressman analysis produces disc-shaped spurious patterns of snow in northern Asia related to the Cressman interpolation. The OI presents a smoother and more correct snow analysis without spurious patterns. The Optimal Interpolation analysis makes a better use of

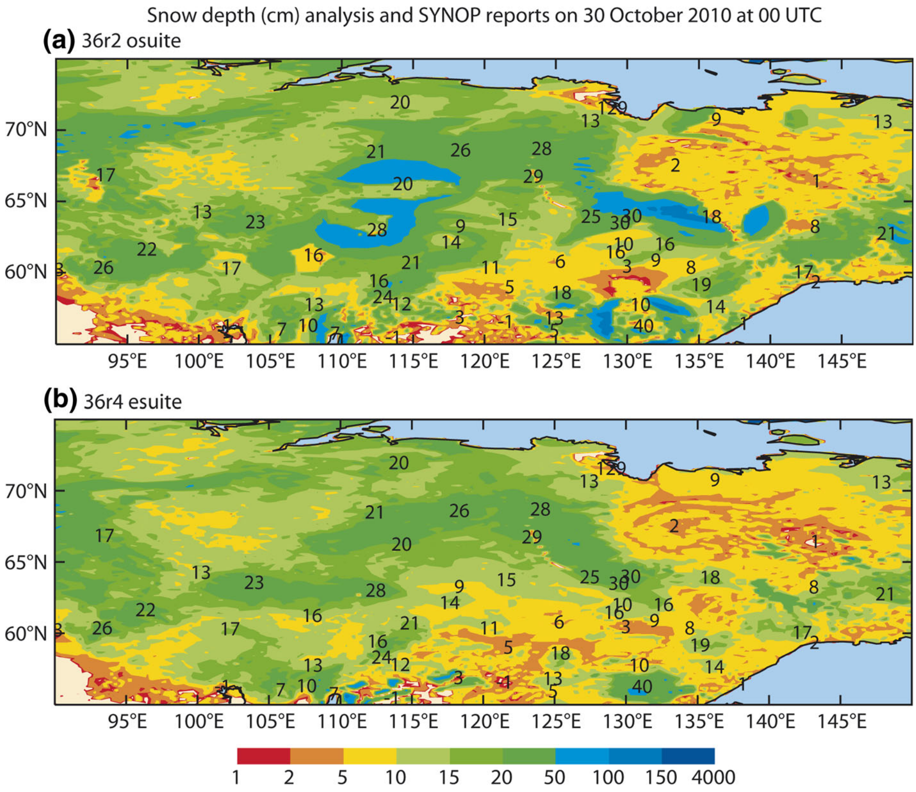

Fig. 1 Snow depth (cm) fields obtained using (*top*) a Cressman snow analysis from the operational ECMWF Integrated Forecasting System and (*bottom*) an OI snow analysis as tested at ECMWF before operational implementation, in northern Asia on 30 October 2010. SYNOP snow depth measurements are reported (cm) in *black* on the figure

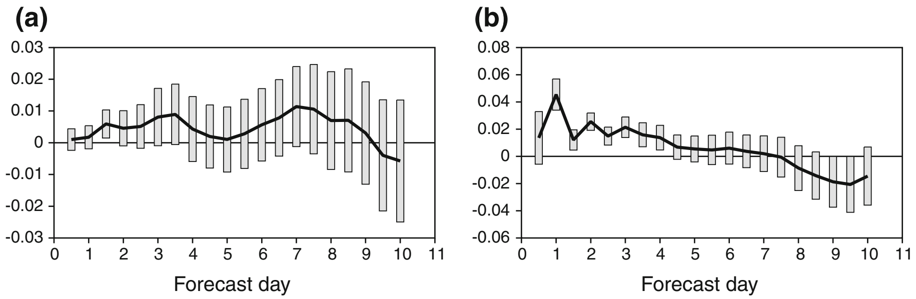

Fig. 2 Normalised root mean square forecast error difference for the ECMWF 1,000 hPa geopotential for (**a**) Cressman minus OI snow analyses, both using the SYNOP reports and the 24-km NOAA NESDIS IMS snow cover product and (**b**) Cressman minus OI, with OI using SYNOP and 4-km NOAA NESDIS IMS snow cover data (new ECMWF snow analysis) and Cressman using SYNOP and the 24-km IMS product (old ECMWF snow analysis). Statistics are computed based on daily analyses at 00 UTC from 01 December 2009 to 28 February 2010. *Vertical bars* show the 90 % confidence interval. The *x*-axis shows the forecast range from 0 to 10 days. Positive impact of the OI analysis compared to the Cressman analysis is shown by positive values

SYNOP snow depth data than Cressman. The difference between the two analyses mainly results from differences in the structure functions between OI and Cressman.

The 2009/2010 winter season, with cold and snowy conditions in the northern hemisphere (Cohen et al. 2010), highlighted the importance of good-quality snow analysis (de Rosnay et al. 2011b). Figure 2 shows the impact of different snow analysis configurations on the forecast 1000 hPa geopotential height error for the winter 2009–2010. Figure 2a shows the impact of the OI snow analysis compared to the Cressman snow analysis, with both schemes using SYNOP and IMS snow cover data at 24 km resolution. Figure 2b shows the impact of the revised ECMWF analysis implemented in 2010 compared to the previous analysis. The old analysis uses Cressman and observations from the SYNOP network and the IMS 24 km product. The new analysis relies on the OI and uses observations from SYNOP and the 4-km snow cover IMS product. The new analysis also accounts for an improved pre-processing and quality control of the IMS NESDIS data. In particular, based on an altitude threshold of 1500 m, the use of the IMS data is switched off in mountainous areas. Replacing the Cressman snow analysis by the OI has a relatively neutral impact on the atmospheric circulation, although a slight non-significant improvement can be seen (Fig. 2a). The new ECMWF snow analysis (Fig. 2b) has an overall positive impact on the atmospheric forecasts skill, with root mean square error forecast for the 1000 hPa geopotential height improved by 1–4 % in the short range (forecasts until day 4). Figures 1 and 2 illustrate that the combined improvements of the analysis approach (OI vs Cressman) and data pre-processing and quality control (IMS snow cover product resolution and altitude threshold) lead to improve both the snow depth fields and the low-level atmospheric forecast.

3 Soil Moisture Analysis

3.1 History of Soil Moisture Analysis for NWP

In the absence of a near-real-time global network for providing soil moisture information, using screen-level data has been the only source of information that has been continuously available from the SYNOP network for NWP soil moisture analysis systems. As shown by Mahfouf (1991), it provides indirect, but relevant information to analyse soil moisture. So, most of the current operational soil moisture analysis systems rely on analysed screen-level variables (2-m temperature and relative humidity).

In 1994, a nudging approach was implemented at ECMWF to analyse soil moisture, using the lowest atmospheric level specific humidity analysis increments. It was the first NWP centre to implement a soil moisture analysis scheme, mainly to prevent the soil moisture from drifting to unrealistic dry conditions in summer time. However, the nudging scheme was not accounting for processes that modulate the relation between soil moisture and specific humidity. So, soil moisture increments were affected by systematic biases with successive negative and positives increments at both the diurnal and seasonal scales (Mahfouf et al. 2000).

In 1999, the nudging soil moisture analysis was replaced by a 1D Optimal Interpolation analysis, as originally proposed by Mahfouf (1991). The OI soil moisture analysis implementation at ECMWF and evaluation are detailed in Douville et al. (2000) and Mahfouf et al. (2000). The OI soil moisture analysis relies on the relation between soil moisture and screen-level temperature and relative humidity. When soil moisture is underestimated, air temperature is expected to be overestimated and air humidity underestimated. In contrast, when soil moisture is overestimated, screen-level air temperature is too low and air humidity too large. Based on this relation between soil moisture and screen-level parameters, the soil moisture correction is computed as a function of the screen-level parameters correction. So, a dedicated screen-level parameters analysis was implemented, based on an OI approach, and its increments are then used as input of the soil moisture analysis (Mahfouf et al. 2000). The same method has been used to analyse soil temperature and snow temperature using the screen-level air temperature increments. The OI soil moisture and temperature analysis has been widely used for NWP applications in several NWP centres. It was used at ECMWF for operational NWP from July 1999 to November 2010. It has been used in ECMWF re-analyses ERA-40 (Uppala et al. 2005) and is still in use for ERA-Interim (Dee et al. 2011). An OI soil moisture analysis is currently used at Météo France (Giard and Bazile 2000), Environment Canada (Bélair et al. 2003) and in the High Resolution Limited Area Model (HIRLAM) (Rodríguez et al. 2003).

As shown by Drusch et al. (2009), the OI soil moisture analysis improves screen-level parameters forecasts, without, however, any positive impact on soil moisture. Furthermore, an important weakness of the OI approach is its lack of flexibility to easily account for new types of data including new generations of satellite data (Mahfouf et al. 2009). Also, it uses calibrated coefficients that would require to be updated for each change in the LSM. The OI, by using fixed coefficients, does not account for local processes such as cloud cover or soil moisture conditions that influence the coupling strength between soil moisture and screen-level parameters and therefore the magnitude of the increments (de Rosnay et al 2012).

Several NWP centres started to investigate the use of satellite data to analyse 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. 2002, 2008). At Météo France, an offline EKF approach was evaluated, and the impact of ASCAT (Advanced SCATterometer) soil moisture data assimilation on the low-level atmospheric parameters was addressed (Mahfouf 2010). A limited impact of the EKF soil moisture analysis on relative humidity and air temperature was found. A simplified Extended Kalman Filter (EKF) soil moisture analysis, using screen-level parameters information, was implemented operationally at the German

Weather Service (Deutscher Wetterdienst) in 2000 (Hess 2001). Along the same line, ECMWF developed a point-scale simplified EKF soil moisture analysis (Seuffert et al. 2004). Preliminary investigations at local scale showed that the OI and the EKF soil moisture analyses give similar results when they both use screen-level parameters (Seuffert et al. 2004). The ECMWF simplified EKF soil moisture analysis was extended to be used at global scale (Drusch et al. 2009) and implemented in operations in 2010 (de Rosnay et al. 2012).

In the following section, differences between EKF and OI soil moisture analyses are presented in terms of soil moisture increments and low-level atmospheric parameters forecasts.

3.2 Comparison Between the OI and EKF Soil Moisture Analyses

de Rosnay et al. (2012) quantified monthly mean global soil moisture increments for both the OI and the EKF schemes for an entire annual cycle. They showed that the OI scheme systematically adds water to the soil. The global monthly mean value of the OI analysis increments was shown to be 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 in increments between the EKF and the OI is mainly due to a systematic 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 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). Figure 3 illustrates monthly mean increments accumulated in the first metre of soil, for August 2009. In agreement with de Rosnay et al. (2012), it shows that larger increments are accumulated into the soil with the OI than with the EKF analysis scheme. It is, however, interesting to note that large increments remain with the EKF in the US Great Plains and in South America, showing these regions are affected by systematic soil moisture bias in the LSM. Further investigation will be carried out in the future to address this feature.

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) (Calvet et al. 2007). de Rosnay et al. (2012) showed 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, with mean correlation between ECMWF and ground truth soil moisture higher than 0.84 when the EKF soil moisture analysis is used (de Rosnay et al. 2012).

Figure 4 shows the monthly mean impact of the EKF soil moisture analysis on the 36-h forecast of 2-m temperature at 0000 UTC for July-August-September 2009. It shows the difference in temperature error (in K) between the OI and EKF experiments. Positive values indicate that the EKF generally improves the 2-m temperature forecasts compared to the OI soil moisture analysis. It is consistent with the results shown by de Rosnay et al. (2012) to indicate that in most areas the 2-m temperature errors for OI are larger than the

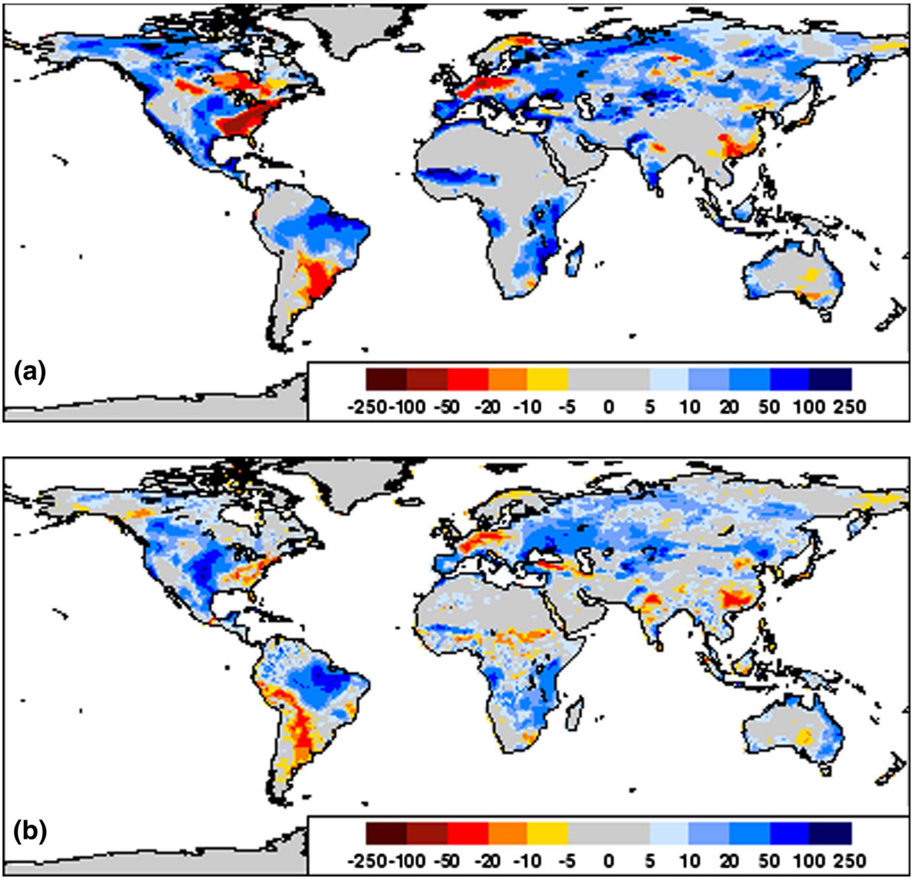

Fig. 3 Accumulated soil water increments (in mm) in the first metre of soil for August 2009, with the OI (*top*) and EKF (*bottom*) analyses

EKF errors, showing that the EKF soil moisture analysis has a slight positive impact on the 2-m temperature forecast.

3.3 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 to NWP models. The active sensor ASCAT on MetOp was launched in 2006 (Bartalis et al. 2007). The EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) ASCAT surface soil moisture product is the first operational soil moisture product. It is available in near-real time, and it has been monitored operationally at ECMWF since September 2009 (de Rosnay et al. 2012). Scipal et al. (2008) evaluated 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 assimilation), ASCAT soil moisture data

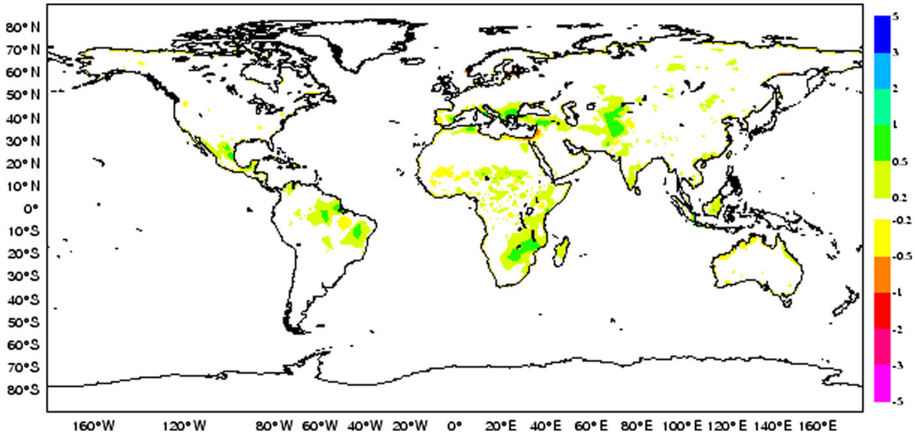

Fig. 4 Mean difference of monthly mean 36-h forecasts (12 UTC) error in 2-m temperature (in K) between the OI and the EKF soil moisture analysis schemes for July–August–September. *Greenish colours* indicate an improvement of the EKF compared to the OI, while *reddish colours* indicate a degradation

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) evaluated 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 UKMO, Dharssi et al. (2011) investigated ASCAT surface soil moisture data assimilation using a simple nudging scheme, as already used at the UKMO to analyse 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. 2007). Based on L-band passive microwave measurements, SMOS is the first mission dedicated to soil moisture remote sensing. The future NASA (National Aeronautics and Space Administration) 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). Work toward assimilation of SMOS data over land is ongoing.

An extensive evaluation and comparison between SMOS, ASCAT and ECMWF soil moisture was conducted by Albergel et al. (2012), using existing soil moisture networks in Europe, Africa, Australia and the USA. Using more than 200 stations to evaluate the remotely sensed and analysed soil moisture products in contrasted climate conditions, the authors showed that (1) SMOS and ASCAT soil moisture products are of similar quality, with annual mean correlation 0.53 for ASCAT and 0.54 for SMOS, and (2) the analysed product is of better quality than the satellite products with 0.70 averaged correlation value.

Draper et al. (2012) recently investigated combined data assimilation, using an Ensemble Kalman Filter, of active and passive soil moisture satellite data. They evaluated the impact of soil moisture products data assimilation on the analysed soil moisture. They showed that, although correlation with ground data was better for the LSM than for the satellite data, data assimilation still has a positive impact on the analysed soil moisture. Their study confirms the potential of satellite-based soil moisture data for NWP applications.

4 Conclusion

This paper presented the current status of data assimilation systems used to initialise land surface variables for Numerical Weather Prediction. Different approaches used to analyse soil moisture and snow depth in Numerical Weather Prediction (NWP) systems were reviewed. Based on ECMWF experiments, analysis results and atmospheric forecast impact were presented for different land surface data assimilation approaches.

Snow processes strongly influence the hydrological cycle, and they have a large impact on the energy budget. So, accurate initialisation of snow depth for NWP applications is highly relevant. Snow analysis schemes currently used for operational NWP rely on simple approaches. Using the NOAA IMS snow cover product, a simple update approach is used at the UKMO. The NCEP latest reanalysis and the GLDAS also use a simple update approach using combined IMS/SNODEP products and the MODIS snow cover product, respectively. The German meteorological service relies on a Cressman interpolation and used the SYNOP snow depth reports. Since 1999 the Canadian Meteorological Center uses a 2D Optimal Interpolation to assimilate SYNOP snow depth observations. At ECMWF both SYNOP observations and the IMS snow cover data are assimilated. A Cressman Interpolation was used for more than 20 years before it was recently replaced by an Optimal Interpolation in 2010.

A qualitative comparison between snow depth fields illustrated differences between the Cressman and the Optimal Interpolation snow depth analyses. In contrast to Cressman, the Optimal Interpolation accounts for the model background and the observations errors, which allows to optimally combine model background and observations. So, by improving the structure functions, the Optimal Interpolation makes a better use of the observations than the Cressman interpolation. The quantitative impact of the snow analysis scheme on the atmospheric forecast was illustrated using ECMWF results. The revised ECMWF snow analysis, using an Optimal Interpolation and SYNOP observations combined with the 4-km IMS snow cover data and improved observation pre-processing and quality control, was compared to the old ECMWF snow analysis based on a Cressman interpolation that uses SYNOP and the 24-km IMS snow cover products without quality control. Results showed that the root mean square error forecast of the 1,000 hPa geopotential height in the northern hemisphere is reduced by 1–4 % in the short range (until forecast day 4) for the winter 2009–2010. This significant and large-scale impact of the snow analysis on the atmospheric forecast illustrates the major importance of the snow analysis for Numerical Weather Prediction applications. SWE products from satellite sensors are not yet used in NWP although they have a potential to provide reliable and near-real-time information on snow mass. It is expected that Snow Water Equivalent products quality will be improved in the next few years. Potential future satellite missions such as the proposed ESA CoReH2O mission are expected to provide SWE estimates from space with an improved accuracy compared to current products.

Concerning soil moisture, most NWP centres use a 1-D Optimal Interpolation analysis to initialise soil moisture, based on a dedicated screen-level parameters analysis. Both the German meteorological service and ECMWF use an Extended Kalman Filter soil moisture analysis in operations. The Extended Kalman Filter soil moisture analysis is based on a dedicated screen-level parameters analysis. Whereas the 1D Optimal Interpolation soil moisture analysis uses screen-level analysis increments as input of the soil moisture analysis, the Extended Kalman Filter, as implemented at ECMWF, uses analysed screen-level fields as input observations of the soil moisture analysis. ECMWF experiments showed that the Extended Kalman Filter soil moisture analysis consistently reduces, by 5 mm per month at global scale, the soil moisture increments compared to the Optimal Interpolation, and it slightly improves both soil moisture and screen-level parameters analyses and forecasts. The ECMWF soil moisture analysis evaluation against ground measurements from the SMOSMANIA network showed an improved correlation from 0.78 for the Optimal Interpolation to 0.84 for the Extended Kalman Filter soil moisture analysis. The Extended Kalman Filter analysis also makes it possible to combine screen-level parameters and satellite data, such as ASCAT or SMOS, to analyse soil moisture. Previous results with ASCAT data assimilation were discussed in this paper. ECMWF results showed a neutral impact of ASCAT data assimilation in the Extended Kalman Filter 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. In contrast to other centres, which mainly use Optimal Interpolation or Extended Kalman Filter approaches, the UKMO, soil moisture analysis relies on a simple nudging scheme. ASCAT soil moisture data assimilation was shown to have a positive impact on the screen-level parameters forecast at the UKMO, leading to operational ASCAT soil moisture assimilation from 2010. Developments are ongoing at the UKMO to replace their current nudging scheme by an Extended Kalman Filter approach which will open possibilities to combine different types of observations in their soil moisture analysis.

Kalman Filter–based land surface analysis systems (Ensemble or Extended), used in several NWP centres, either in research or operationally, open a wide range of further development possibilities, including exploiting new satellite surface data and products for the assimilation of soil moisture (e.g., SMOS or the future SMAP). At ECMWF an extension of the Extended Kalman Filter to analyse additional variables, such as snow temperature, snow mass and vegetation parameters, is planned for investigation in the near future.

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