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ECMWF soil moisture validation activities

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ECMWF soil moisture validation activities

Clement Albergel, Patricia de Rosnay, Gianpaolo Balsamo,
Joaquin Muñoz-Sabater, Souhail Boussetta, Lars Isaksen

The importance of soil moisture in the global climate system has recently been underlined by the Global Climate Observing System (GCOS) Programme endorsing soil moisture as an Essential Climate Variable. It is a crucial variable for weather and climate predictions and plays a key role in hydrological processes. A good representation of soil moisture conditions can help to improve (a) the forecasting of precipitation, droughts and floods, and (b) the making of climate projections and predictions.

In situ measurements of soil moisture are an indispensable source of information for evaluating soil moisture analyses and forecasts. At ECMWF they are used to evaluate the operational soil moisture analysis and the interim reanalysis (ERA-Interim). They also support of the development of new land-surface parametrizations and analysis systems.

In this article we describe the soil moisture validation strategy adopted at ECMWF and present a selection of validation results.

Soil moisture validation strategy

Soil moisture is usually defined as the amount of water present in the unsaturated part of the soil (i.e. between the soil surface and the ground water level) and is generally expressed as the volumetric fraction of water in a given soil depth (m^3 water per m^3 soil). While in the 1990s records of in situ soil moisture measurements were available for only a few regions and often for only short periods, huge efforts were made in recent decades to make available such observations in contrasting biomes (i.e. major ecological communities, extending over a large area and usually characterized by a dominant vegetation) and climate conditions. The establishment of the International Soil Moisture Network (ISMN, http://www.ipf.tuwien.ac.at/in situ/), a new data hosting centre where globally-available ground-based soil moisture measurements are collected, harmonized and made available to users, is a clear indication of the importance attached to making such data available to the scientific community.

ECMWF has collected data from several networks across the world to establish a comprehensive database of in situ soil moisture measurements – some of these networks are illustrated in Figure 1. The database is used to evaluate various soil moisture products from ECMWF's Integrated Forecasting System (IFS).

Figure 2 gives an overview of the SMOSMANIA network in southwestern France, which is extensively used at ECMWF for validation purposes. It is a unique data set; for the first time, automatic measurements of soil moisture have been integrated in an operational meteorological network (i.e. the RADOME network of Météo-France). At those sites, four soil moisture probes were installed at each station at depths of 5, 10, 20 and 30 cm. The probes used the dielectric permittivity properties of the soil to estimate the volumetric soil moisture content – this is a common way to measure soil moisture. Site-specific calibration curves were developed using in-situ gravimetric soil samples to convert the signal from the probe into volumetric soil moisture content. As calibrations have to be performed for each soil type (i.e. for all stations) and for each depth, 48 calibrations curves were obtained for the SMOSMANIA network. The calibration was performed both in situ and in a laboratory (monitoring of a given sample in various controlled conditions).

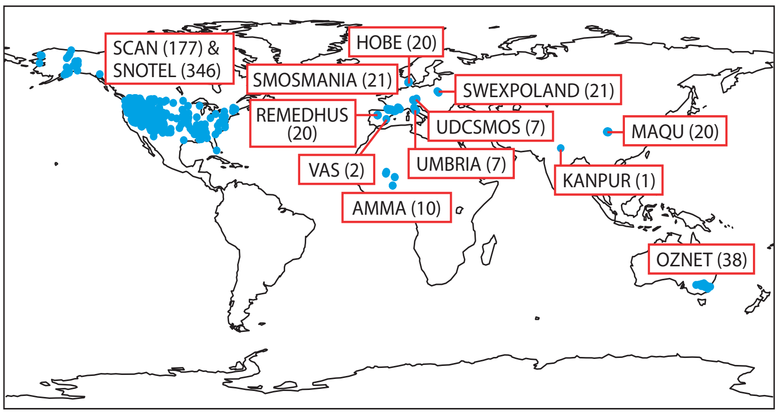

Figure 1 Location of some in-situ soil moisture stations used at ECMWF for validation activities.

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In recent years the land-surface modelling and analysis systems at ECMWF have been extensively revised. An improved soil hydrology, new snow scheme, multi-year satellite-based vegetation climatology and new bare-ground evaporation have been included in the IFS. Also a new soil moisture analysis scheme, based on a point-wise Extended Kalman Filter (EKF) for the global land surface, was developed and implemented. *ECMWF Newsletter No. 127* (12–16, 17–22 and 23–27) described in more detail all these recent upgrades of land-surface processes and analysis affecting soil moisture. As with any updates, it is important to validate their impact.

The in situ data has been used to evaluate soil moisture from ECMWF's operational analysis, ERA-Interim and research experiments (*Albergel et al.*, 2012a,b). While the IFS is updated regularly to improve the analysis and modelling systems, ERA-Interim is produced using a fixed version. In addition, in-situ measurements have been used to evaluate the impact of two specific modifications: the new bare-ground evaporation and the new EKF soil moisture analysis. Table 1 provides more details about the experiments that are being evaluated.

The main metrics used for comparing in situ soil moisture data with model fields are the temporal correlation, bias (in situ minus ECMWF data) and root-mean-square difference (RMSD). Box A presents the validation methodology in detail. The rationale for using the root-mean-square difference instead of root-mean-square error is to emphasise that in situ data may contain errors (instrumental and representativeness) so they are not considered as 'true' soil moisture.

The ECMWF Land Surface Model (LSM) is a multi-layer model where the soil is discretized in four layers with depths of 0.07, 0.28, 0.72 and 2.89 m (from top to bottom). In-situ measurements at corresponding depths are used to evaluate the output from the LSM. For example, observations at a depth of 5 cm are used to evaluate the first layer (0–7 cm).

Soil moisture data set	Type	Period	Spatial resolution (as from Jan. 2007)	Land Surface Model IFS cycle***
ECMWF operational analysis	Analysis	Jan. 2007 to May 2012	Before 26 Jan. 2010: 23 km (T799) From 27 Jan. 2010: 16 km (T1279)	Cy31r2 to Cy37r3
ERA-Interim	Reanalysis	Jan. 2007 to Dec. 2012	80 km (T255)	Cy31r1
BEVAP-NEW	Surface-only simulations*	Jan. 2007 to Dec. 2010	80 km (T255)	Cy36r4
BEVAP-OLD	Surface-only simulations*	Jan. 2007 to Dec. 2010	80 km (T255)	Cy36r4 (old bare-ground evaporation)
OI **EKF** **EKF+ASCAT**	Research experiments**	Dec. 2008 to Nov. 2009	80 km (T255)	Cy36r1

Table 1 List of various soil moisture analyses used in this study.

* ERA-Interim near-surface meteorology is used as forcing term; more information in Balsamo et al. (2012).
** More information in de Rosnay et al. (2011).
*** More information at http://www.ecmwf.int/research/ifsdocs/

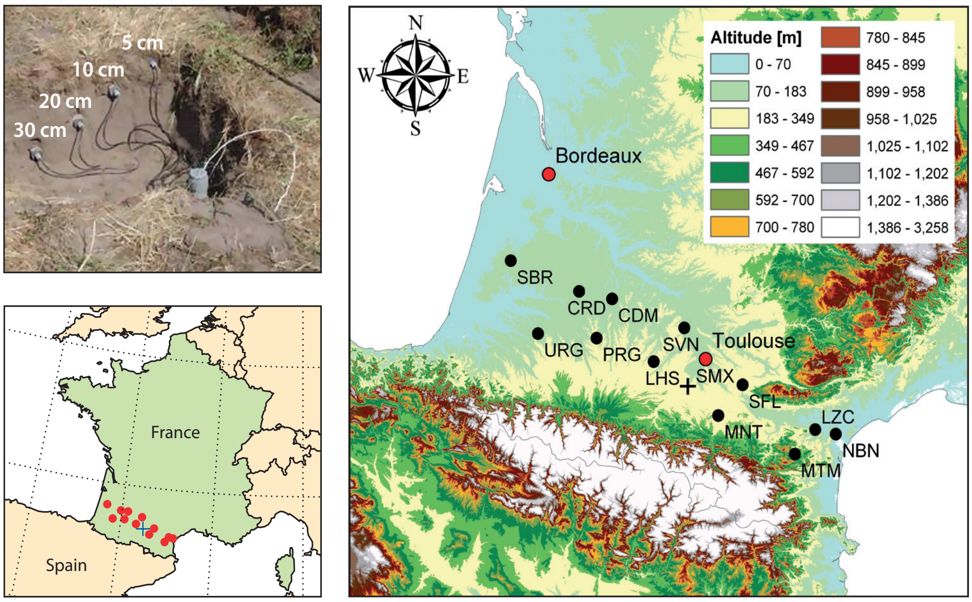

Figure 2 Illustration of the SMOSMANIA network (from Météo-France). In-situ soil moisture measurements from this network were used to evaluate various ECMWF's soil moisture analyses. The digital elevation model (90 m) is from the Consortium for Spatial Information (CGIAR-CSI), http://srtm.csi.cgiar.org. The SMOSMANIA network used ThetaProbe ML2X of Delta-T Devices.

Metrics used for the validation of soil moisture analyses

A

As in situ observations of soil moisture are frequently associated with soil temperature measurements, observations were flagged for temperatures lower than 4°C to avoid frozen conditions.

Comparison of soil moisture time series between in situ observations and ECMWF's soil moisture analysis are based on data at 00 UTC. At each station the correlation (R), bias (in situ minus ECMWF data) and root-mean-square difference ($RMSD$) are computed between observations and soil moisture analyses. Additionally, the ratio between analysed and in situ standard deviations (SDV) and the centred normalized root-mean-square difference between the analysis and in situ patterns (E) are computed.

$$SDV = \sigma_{\text{analyse}} / \sigma_{\text{in situ}}$$
$$E^2 = (RMSD^2 - Bias^2) / \sigma^2_{\text{in situ}}$$

The SDV gives the relative amplitude whilst E quantifies errors in the pattern variations. Note that E does not include any information on biases since the means of the fields are subtracted before computing second order errors.

R, SDV and E are complementary but not independent as they are related by:

$$E^2 = SDV^2 + 1 - 2 \cdot SDV \cdot R$$

Taylor diagrams, like those found in Figure 4, represent these three statistics using two-dimensional plots.

The normalized standard deviation (SDV) is displayed as a radial distance and the correlation with in situ data (R) as an angle in the polar plot.

In situ data are represented by a point located on the horizontal axis at $R = 1$ and $SDV = 1$. The distance to this point represents the centred normalized root-mean-square difference (E) between the analysis and in situ patterns.

The p-value, a measure of the correlation significance, is also calculated. It indicates the significance of the test. Only cases with p-values below 0.05 are considered.

Usually, soil moisture time series show a strong seasonal pattern that could artificially increase the agreement between satellite and in situ observations in terms of R. Therefore, to avoid seasonal effects, monthly anomaly time series are also be calculated. The difference from the mean is calculated for a sliding window of five weeks (if there are at least five measurements in this period), and the difference is scaled to the standard deviation. For each soil moisture estimate at day (i), a period F is defined, with $F = [i - 17, i + 17]$ (corresponding to a five-week window). If at least five measurements are available in this period, the average soil moisture value and the standard deviation are calculated. R is computed for both volumetric and anomaly time series.

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Evaluation of the operational analysis and ERA-Interim

During 2008–2010, averaged statistical scores for the correlation, bias and root-mean-square difference (RMSD) are given below for the operational analysis and ERA-Interim (first layer of soil) when compared to in situ soil moisture from 117 stations across the world under different biome and climate conditions (Europe, USA, West Africa, Australia).

	Operational analysis	**ERA-Interim**
Correlation	0.70	0.63
Bias (m^3m^{-3})	-0.081	-0.079
RMSD (m^3m^{-3})	0.113	0.121

In general, both products captured well the temporal dynamics of the observed soil moisture, though the operational analysis has slightly better scores than ERA-Interim.

Figure 3 illustrates the soil moisture from ECMWF's operational analysis and ERA-Interim, compared to in situ data from two SMOSMANIA stations (Sabres and Lahas) from southwestern France for the period 2007–2010. Until October 2007 the operational and ERA-Interim results are similar, but after the implementation of the H-TESSEL land-surface scheme in operations in November 2007 was a shift in the soil moisture range (e.g. a shift down for Sabres and up for Lahas station). It is clear that, because of the use of H-TESSEL, the operational soil moisture analysis has a larger variability than ERA-Interim which uses the original TESSEL model. Overall the H-TESSEL implementation leads to a larger dynamical range and is in better agreement with the in situ observations.

To assess the ability of ECMWF analyses to capture the short-term soil moisture variability, anomaly time-series were derived and the correlations were computed. For this group of stations, correlations of the anomaly time-series range from 0.29 to 0.61 with an average of 0.51 for the operational analysis and from 0.27 to 0.62 with an average of 0.49 for ERA-Interim. Correlations of volumetric time series are larger than those for the monthly anomaly time-series. This is largely explained by the seasonal variations being suppressed in the monthly anomalies.

Figure 4 shows two Taylor diagrams (see Box A for further detail) illustrating the statistics from the comparison between soil moisture from ECMWF and in situ data for the 12 stations from the SMOSMANIA network during 2008–2010 (the diagram on the left is for the first layer of soil, 0–7 cm and the one on the right is for the first two layers, 0–28 cm). These results show a very high level of correlation between ECMWF soil moisture and in situ data: most values are between 0.70 and 0.90 (as indicated by the angle in the Taylor diagrams). Also, they show that the variability of ERA-Interim (red dots), which is gauged by the normalised standard deviation (SDV), is smaller than that of the operational analysis (black dots) compared to in situ data (as indicated by the radial distance in the Taylor diagrams). Also the ERA-Interim analysis has SDV values that are systematically lower than 1 (i.e. the red dashed line). This indicates that the variability of the in situ data is higher than for ERA-Interim. Although, both the operational analysis and ERA-Interim show good skills in capturing the variability of surface soil moisture, they tend to overestimate soil moisture, particularly for dry land. This is consistent with the statistical scores presented above.

Overestimation of soil moisture by ECMWF compared to in-situ observations might be caused by shortcomings in the models representation of soil textures, and by the difficulty of representing the heterogeneity of soil moisture. The spatial variability of in situ soil moisture is very high and differences in soil properties could imply differences in its mean and variance.

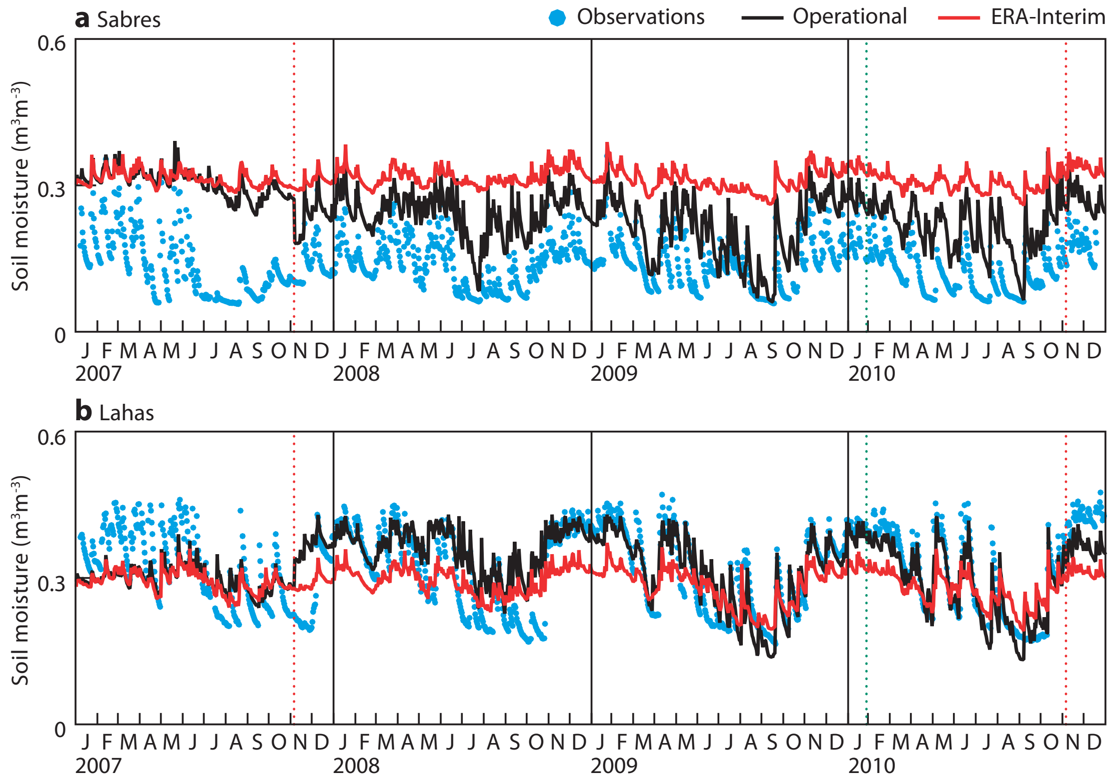

Figure 3 Soil moisture time series for the first layer of soil (0–7 cm) for 2007–2010 for two stations of the SMOSMANIA network: (a) Sabres and (b) Lahas. Results are shown for in situ observations, the ECMWF's operational analysis and ERA-Interim. Dashed vertical lines indicate major changes in the operational system affecting soil moisture: in November 2007 the implementation of H-TESSEL, in January 2010 a change in the spatial resolution from 23 km (T799) to 16 km (T1279) and in November 2010 the implementation of the EKF soil moisture analysis and bare-ground evaporation parametrization.

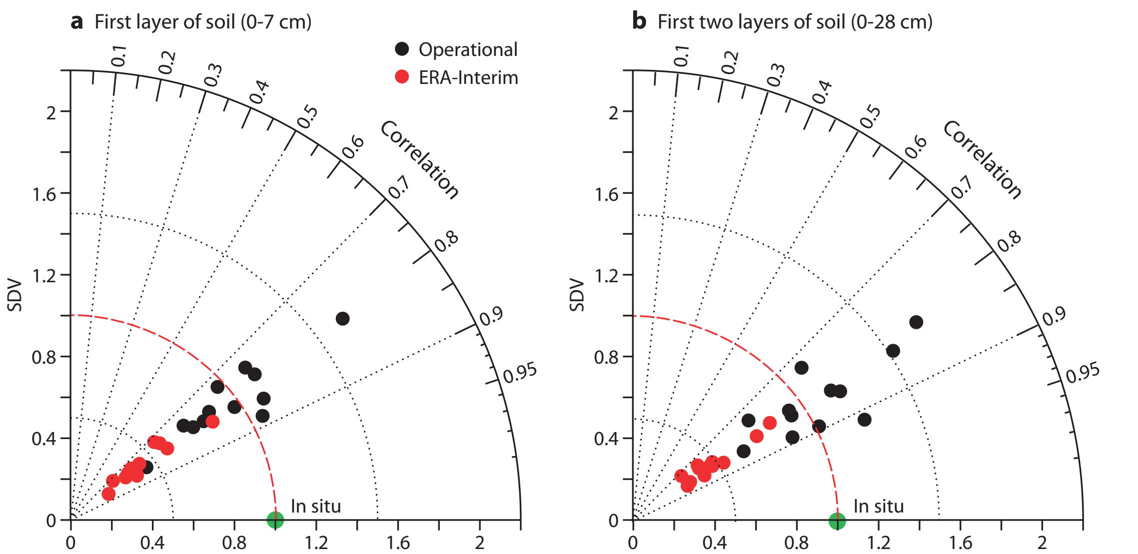

Figure 4 Taylor diagrams illustrating the statistics from the comparison between ECMWF's operational analysis and ERA-Interim reanalysis against in situ observations for (a) first layer of soil (0–7 cm) and (b) first two layers of soil (0–28 cm) and in situ observations from the SMOSMANIA network for 2008–2010. Symbols indicate at each station the correlation (angle), normalized SDV (radial distance to the origin point), and normalized centred root-mean-square error (distance to the green point marked "In situ") between the ECMWF analysis and in situ data. The red, dashed line indicates an SDV value of 1.

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Support for the new land-surface parametrization

In situ soil moisture data from 122 stations across the United States from SCAN (Soil Climate Analysis Network) were used to evaluate the impact of a new bare-ground evaporation formulation described by *Balsamo et al.* (2011) and *Albergel et al.* (2012b). This model upgrade produces more realistic soil moisture values when compared to in situ data, particularly over bare-ground areas.

Two experiments were run.

- *BEVAP-NEW*: Used the new bare-ground evaporation formulation.
- *BEVAP-OLD*: Used the old bare-ground evaporation formulation and acted as the control.

More information about these experiments is given in Table 1.

Considering the field sites with a fraction of bare ground greater than 0.2 (according to the model), the RMSD of soil moisture is shown to decrease from 0.118 m^3m^{-3} to 0.087 m^3m^{-3} when using the new bare-ground evaporation in research experiments, and from 0.110 m^3m^{-3} (in 2010) to 0.088 m^3m^{-3} (in 2011) in operations. The new scheme also improves correlations.

Figure 5a illustrates the results from BEVAP-NEW and BEVAP-OLD as well as the in situ observations for one site located in Utah (USA) with a bare-ground fraction of 0.7. Minimum values of BEVAP-OLD soil moisture are limited by the dominant wilting point for vegetation types; however ground data indicate much drier conditions, as is clearly observed from May to September 2010. The new bare-ground evaporation allows the model to go below this minimum value so BEVAP-NEW soil moisture is in much better agreement with the observations than that of BEVAP-OLD. Along with the decrease in RMSD, the correlation is increased from 0.63 to 0.65. Also BEVAP-NEW has a more realistic decrease in soil moisture after precipitation events due to its higher water holding capacity; this explains the slightly better correlations.

Figure 5b shows the operational analysis over 2010–2011. It is in much better agreement with the observations after the implementation of the new bare-ground evaporation in November 2010; this is particularly clear for the period from May to September. Considering the short-term variability, this is similar in both experiments with the average correlations for the monthly anomaly time series being 0.54 for BEVAP-OLD and 0.55 for BEVAP-NEW.

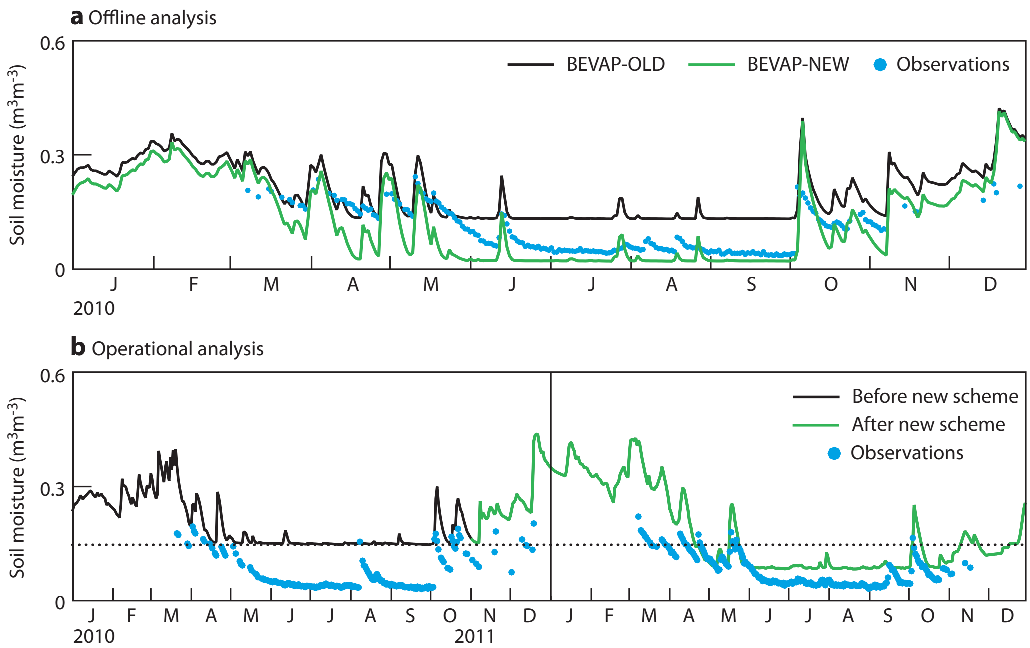

Figure 5 Surface soil moisture time series for two sites in Utah from the SCAN network. (a) Offline analysis at a site in Utah over 2010 for one-surface only simulation without the new bare-ground evaporation formulation (BEVAP-OLD) and with the new formulation of bare-ground evaporation (BEVAP-NEW; also shown are in situ observations. (b) The operational soil moisture analysis for another site in Utah during 2010–2011. The black line becomes green when the new bare-ground evaporation formulation is implemented in November 2010. Also shown are the in situ observations of surface soil moisture. The horizontal dotted line represents the model's minimum soil moisture limit before the implementation of the new bare-ground evaporation (permanent wilting point).

Support for the new soil moisture analysis: Extended Kalman Filter

P. de Rosnay et al. (2011) investigated the impact of the new EKF analysis compared to the previous Optimal Interpolation (OI) scheme. It was found that the new scheme slightly improved both soil moisture and screen-level parameters (analyses and forecasts) when verified against independent observations (e.g. correlation of 0.80 between the OI analysis and in situ data from the SMOSMANIA network from December 2008 to November 2009, but 0.84 when using the EKF). Also the EKF analysis has a stronger impact on the soil moisture of the second layer of soil.

The EKF scheme makes it possible to combine screen-level parameters and satellite data to analyse soil moisture. While EKF assimilations using remotely-sensed soil moisture from ASCAT show a neutral impact on both soil moisture and screen-level parameters, recent improvements in the ASCAT soil moisture products are expected to enhance its impact on the soil moisture analysis.

ERA-Interim and surface-only simulations

ECMWF recently developed a system to run surface-only simulations; it permits the updating of the land-surface component of the ERA-Interim reanalysis (Balsamo et al., 2012). With this approach, the ERA-Interim near-surface meteorology is used as a forcing term to constrain various LSMs used in the IFS. For example, BEVAP-NEW is one of these surface-only simulations – it uses the LSM in IFS cycle 36r4 forced by ERA-Interim near-surface atmospheric fields.

Now consider two soil moisture networks (SMOSMANIA in France and SCAN in the USA) and two soil moisture analyses from ECMWF (ERA-Interim and BEVAP-NEW). In this case various comparisons are performed.

- The first layer of ECMWF soil moisture (0–7 cm) is compared to observations at a depth of 5 cm.
- ECMWF soil moisture integrated over the two first layers (0–28 cm) is compared to averaged observations (5, 10, 20 and 30 cm) from the SMOSMANIA network.
- ECMWF soil moisture integrated over the first three layers (0–100 cm) is compared to averaged observations (5, 20 and 50 cm) from the SCAN network.

As an illustration, Figure 6 shows the comparison of ERA-Interim and BEVAP-NEW with the Montaut station belonging to the SMOSMANIA network for the first layer of soil (top panel) and the integrated first two layers (bottom panel). Detailed statistical scores are given in Table 2. Correlations and RMSD are slightly better when considering the first two layers (0–28 cm). Similar results were found with stations of the SMOSMANIA network in southwestern France and from the SCAN network over the USA (but with slightly lower scores for SCAN).

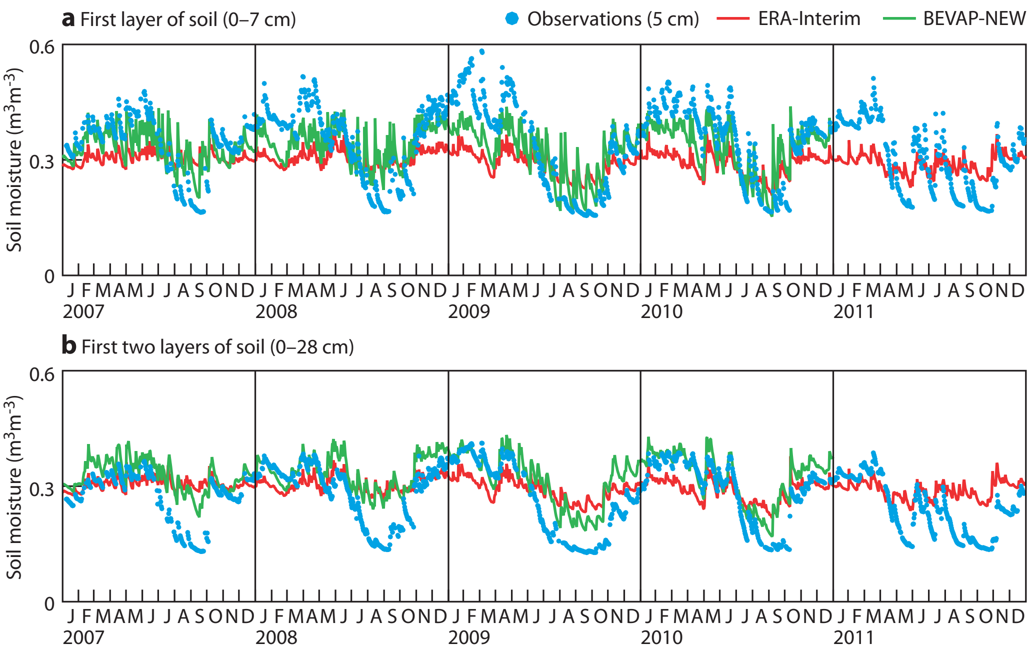

Figure 6 Illustration of soil moisture time series for (a) first layer of soil (0–7 cm) and (b) first two layers of soil (0–28 cm) from in situ data, ERA-Interim and BEVAP-NEW for the Montaut station belonging to the SMOSMANIA network in southwestern France.

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Soil moisture data set	SMOSMANIA (France)				SCAN (USA)			
	First layer, first two layers: 12 stations in each				First layer: 153 stations, first three layers: 137 stations			
	ERA-Interim		BEVAP-NEW		ERA-Interim		BEVAP-NEW	
	First layer	First two layers	First layer	First two layers	First layer	First three layers	First layer	First three layers
Correlation	0.75	0.81	0.79	0.85	0.57	0.61	0.64	0.70
Bias (m^3m^{-3})	0.040	0.045	0.058	0.060	0.054	0.024	0.056	0.048
RMSD (m^3m^{-3})	0.099	0.086	0.091	0/080	0.111	0.093	0.124	0.104

Table 2 Results of the comparisons between in situ observations and soil moisture analyses from ERA-Interim and BEVAP-NEW for 2007–2010. Mean correlation, bias and root-mean-square difference (RMSD) are given for two networks and for two layers: first layer covering 0–7 cm versus observations at 5 cm for both networks and first two layers covering 0–28 cm versus averaged observations at 5, 10, 20, 30 cm for SMOSMANIA and first three layers covering 0–100 cm versus averaged observations at 5, 20 and 50 cm for SCAN.

Latest operational soil moisture evaluation

Finally, the first layer of ECMWF's operational soil moisture analysis is evaluated in the USA (SCAN and SNOTEL networks) over the most recent period, January 2011 to April 2012. For this period, no significant model and analysis changes affected the soil moisture. An averaged correlation value of 0.70 is found for both networks. These results, plus those given in the following table, underline the good quality of the ECMWF's operational soil moisture analysis.

	SCAN	SNOTEL
Number of stations	149	257
Correlation	0.70	0.70
Bias (m^3m^{-3})	0.071	0.100
RMSD (m^3m^{-3})	0.123	0.141

Summary

A database of in situ soil moisture observations from several networks across the world, under different biome and climate conditions, was used to evaluate various ECMWF soil moisture analyses. They were shown to capture well the temporal dynamics of observed soil moisture, both in term of annual cycle and short-term variability.

All the recent updates in the land-surface modelling and analysis systems are shown to contribute to improved representation of soil moisture.

It has been shown in this article how the in situ soil moisture database gathered at ECMWF makes it possible to validate the soil moisture analysis, and how it also can be used to evaluate the impact of modifications of the land-surface parametrization and the analysis system.

Further reading

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