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Calibration and downscaling of seasonal soil moisture forecasts using satellite data

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Abstract

A new approach to calibrate and downscale soil moisture forecasts from the seasonal ensemble prediction forecasting system of ECMWF is presented in this study. Soil moisture forecasts from this system are rarely used nowadays though they could provide valuable information. Weaknesses of the model soil scheme in forecasting soil water content are the main reason why soil water information is not used so far. The basic idea to overcome some of the modelling problems is the application of additional information provided by two satellite measurement systems (ASCAT and ENVISAT ASAR) to improve the forecast quality. Seasonal forecasts from 2011 and 2012 have been compared to in-situ measurements sites in Kenya to test the approach. Results confirm that both the calibration and the downscaling can add skill to the forecasts.

1 Introduction

Proper knowledge of soil water content and distribution is important for many applications in earth system sciences. Soil moisture has a significant impact on near-surface parameters like temperature and humidity, low clouds and precipitation by influencing the exchange of heat and water between the soil and the lower atmosphere (Ferranti and Viterbo, 2006; Dharssi et al., 2011). Evapotranspiration, infiltration and runoff depend on soil wetness, as does the sensible heat flux from the surface and the heat stored in soils. Soils provide nutrients for the biosphere, and soil water is also important in biogeochemical cycles (Zreda et al., 2012).

Unfortunately, soil water content is difficult to measure. This is due to the high variability of soil water content both in time and space, even over short distances (Western et al., 1999), which makes it difficult to establish a useful in-situ measurement network. Though there is an initiative for such a network (Dorigo et al., 2011), satellite measurements are preferred in many applications for their global coverage, spatial representativeness and near real-time availability.

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Due to the processes described above, the need for proper soil moisture representation in modelling is well understood. Nevertheless, simplifications in the representation of modelled land-surface processes in numerical models are unavoidable. They lead to systematic errors in the soil moisture field which is degrading forecast quality (Drusch and Viterbo, 2007). This is the main reason why (seasonal) soil moisture forecasts are not used nowadays although it could be valuable information. Especially in hydrological applications, including flood forecasting and drought monitoring, one is interested in the root zone soil moisture at the catchment or finer scales as its knowledge can significantly improve estimates (Wagner et al., 2007). This in turn is necessary for agricultural and food security issues as well as disaster management. To partly overcome the problem of low forecast representativeness and accuracy, a new method to calibrate seasonal soil moisture forecasts of the ECMWF ensemble forecasting system is presented in this paper. Furthermore, a downscaling approach is tested to provide high-resolution soil water forecasts.

Data sources used for the investigation are described in Sect. 2. Section 3 includes the calibration and downscaling approach, and in Sect. 4 the results are presented. Conclusions are drawn in Sect. 5, including an outlook on future work and applications.

2 Data sources

Seasonal forecasts as well as reference forecasts of soil moisture are generated at the European Centre for Medium-Range Weather Forecasts (ECMWF). Soil moisture measurements are available from satellite platforms and in-situ measurement sites in the testing region in Kenya. In the following subsections, the data sources are described in detail.

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2.1 ASCAT soil moisture data

The Advanced Scatterometer (ASCAT) is a C-band (5.255 GHz) real aperture radar operated by EUMETSAT (European Organization for the Exploitation of Meteorological Satellites). It is flown on the METOP satellites. Near-real-time (about 2 h after sensing) ASCAT surface soil moisture maps at 25 and 50 km spatial scale are available operationally since December 2008 (Wagner et al., 2010). ASCAT soil moisture data used for this study have been provided by Vienna Technical University (status April 2012). As the data are stored as time series for single grid points, they were interpolated to the ECMWF model grid (0.7° resolution) to be comparable. To do this, an inverse distance weighting approach (Shepard, 1968) was used. ASCAT soil moisture data are available in %, i.e. they take values between 0 (dry limit) and 1 (moist limit), thus all other data sources have to be recalculated to this range to be comparable. ASCAT soil moisture is valid for the surface soil layer with an approximate depth of 1–2 cm. Quality flags for wetlands, snow cover, frozen soil and topographic complexity (Scipal, 2005) have been considered. For the ASCAT grid points investigated over the target region, none of the flags had values which would have made it necessary to reject measurements.

2.2 Seasonal forecast data from ECMWF

Seasonal forecasts used for this comparison are produced by the Seasonal Ensemble Prediction System (EPS) of ECMWF. System 4 (Molteni et al., 2011), which was used in this study, is in operational use since 2011. For the atmospheric part of the forecasting system, ECMWFs Integrated Forecasting System (IFS) is used with a horizontal resolution of about 0.7 degrees and 91 vertical levels with a model top at ∼ 0.01 hPa. Soil processes are modeled by H-TESSEL (Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land; Balsamo et al., 2009, 2011). Data output for soil moisture is provided 24-hourly for 4 vertical soil levels: 0–7, 7–28, 28–100, 100–289 cm. The seasonal forecasts include 51 ensemble members. Forecast runs are started at 00:00 UTC on the 1st of each calendar month with a lead time of 215 days (5160 h). Data have

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been extracted from MARS (Meteorological Archival and Retrieval System; ECMWF, 2013a) for 4 × 4 grid points in Kenya.

In order to compare ECMWF output and ASCAT data, the ECMWF data unit has to be transformed from the original volumetric soil water [$m^3\,m^{-3}$] to an index with values between 0 and 100 (saturation fraction or soil water index (SWI)). H-TESSEL distinguishes between six different soil types. Using these soil types, for each of the grid points the SWI in % has been calculated for the combined 1st and 2nd soil layer with

$$\mathrm{SWI} = \frac{0.25\,\mathrm{SWL}_1 + 0.75\,\mathrm{SWL}_2}{\mathrm{SWL}_{\mathrm{SAT}}} \cdot 100, \qquad (1)$$

where $\mathrm{SWL}_{\mathrm{SAT}}$ [$m^3\,m^{-3}$] is the saturation value for the grid point (solely depending on the soil type). SWL_i [$m^3\,m^{-3}$] is the forecasted volumetric soil water of the ith layer at the grid point.

2.3 Reference forecasts from ECMWF

The reference ensemble is created out of historical IFS analyses of the operational high resolution forecasting system at ECMWF. This reference is used to quantify if the seasonal forecasting system has a prediction skill higher than a climatological forecast. Soil moisture data from 00:00 UTC runs for January 2001 to December 2012 from the two upper layers of the H-TESSEL soil scheme have been extracted from the MARS archive to ensure a model climatology with sufficient robustness for comparison. As the resolution of the IFS deterministic run (0.125°) is significantly higher than the seasonal EPS's one, grid points with corresponding location to the 16 grid points in Kenya have been selected.

The analyses for all the years extracted have been combined, and as a result, a 12-member poor-man ensemble for each of the sixteen model grid points is available as reference forecast. Equation (1) has been applied to this data set, too.

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2.4 COSMOS station data

To quantify the forecast quality of the ECMWF seasonal forecasts, two in-situ measurement sites in Kenya have been used. They are part of COSMOS (COsmic-ray Soil Moisture Observing System). The stationary cosmic-ray soil moisture probe measures the neutrons that are generated by cosmic rays within air and soil and other materials, moderated by mainly hydrogen atoms located primarily in soil water. The neutrons are emitted to the atmosphere where they mix instantaneously at a scale of hundreds of meters. Their density is inversely correlated with soil moisture (Zreda et al., 2012). Figure 1 shows the location of the two probes which are operated by the University of Arizona. Data are freely available on a web page (http://cosmos.hwr.arizona.edu) and have been downloaded for the period 2011 to 2012. Measurements at the two stations are representative for a soil layer of 15–30 cm (depending on the current soil water content), so on average they are representative for the same soil depth as the combined H-TESSEL layer 1 (0–7 cm) and layer 2 (7–28 cm) data calculated in Eq. (1). COSMOS stations are measuring average soil water content within a diameter of a few hectometers (Zreda et al., 2012).

COSMOS level-3 soil moisture data (Zreda et al., 2012) are provided in volumetric soil moisture [$m^3\,m^{-3}$]. They were transformed to relative values between 0 and 100 by taking the lowest (highest) value in the measurements time series as 0 (100) and rescaling all measurements between these two values.

Both COSMOS stations (KLEE: 36.867° E/0.283° N, Mpala-North: 36.87° E/0.486° N) are within the same IFS grid cell (0.7° resolution of the seasonal EPS), but the nearest grid point which is used for the comparison is different (37.1° E/0.0° N vs. 37.1° E/0.7° N).

3 The calibration and downscaling approach

To downscale seasonal soil moisture forecasts from the global grid to a 1 km resolution, a two-step approach is necessary. In a first step, the forecast climatology is calibrated, meaning that it has to be shifted to the ASCAT climatology. This is done with a CDF matching approach (Reichle and Koster, 2004). After this calibration, the relationship between ASCAT and ENVISAT ASAR can be applied to the seasonal soil moisture forecasts in a second step to gain results on the 1 km grid.

3.1 Step 1: calibration with CDF matching

To match ASCAT and ECMWF cumulative distribution functions, for each global model grid point (within the selected domain) the daily IFS/EPS forecast values of each ensemble member are compared to the available ASCAT measurements. As the forecasting model for each IFS/EPS member is the same, the number of ASCAT-IFS/EPS data pairs can be increased by the factor of 51 which makes the results more robust from the statistical point of view. Data from 7 consecutive seasonal runs (starting dates 1 October 2011 to 1 April 2012) are compared. Based on these data pairs, a polynomial regression analysis is applied to the data set. Polynomials up to the ninth degree have been tested. It was found out that beside the linear regression all polynomials are reasonable for the bias correction. Comparing the mean of ASCAT with the means of IFS/EPS before and after the CDF matching, 4th order polynomials for the correction turned out to be the most proper one (i.e. the corrected IFS/EPS mean is fitting best to the ASCAT mean), followed by 8th and 3rd order polynomials. Thus it was decided to use 4th order polynomials as they are taking into account the most relevant statistical moments of expectation, variance, skewness and kurtosis. The CDF matching has been applied both to seasonal (EPS) and reference (IFS) forecasts.

3.2 Step 2: applying the ASCAT – ENVISAT ASAR relation

For the disaggregation of coarse scale microwave measurements, finer resolution satellite data acquired e.g. by synthetic aperture radars (Das et al., 2011) are applied (Wagner et al., 2013). For 25 km ASCAT soil moisture data, Advanced Synthetic Aperture Radar (ASAR) data acquired by the ENVISAT satellite are used. The method exploits the fact that the temporal dynamics of the soil moisture field is often very similar across a wide range of scales. This phenomenon is usually referred to as "temporal stability" (Vachaud et al., 1985), meaning that the relationship between local scale and regional scale measurements may be approximated by a linear model. To estimate soil moisture at 1km scale from the 25 km ASCAT soil moisture data,

$$m_s^{1\,\text{km}}(t,x,y) = c_{\text{ASAR}}(x,y) + d_{\text{ASAR}}(x,y)m_s^{25\,\text{km}}(t), \qquad (2)$$

is used (Wagner et al., 2013).

$m_s^{1\,\text{km}}$ is the estimated surface soil moisture content over the 1 km area centered at the coordinates (x, y). $m_s^{25\,\text{km}}$ is the calibrated ECMWF soil moisture at forecasting time t. Originally, $m_s^{25\,\text{km}}$ is the ASCAT soil moisture retrieval at time t, but due to the calibration in step 1, this replacement with ECMWF model forecast data can be justified. The coefficients c_{ASAR} and d_{ASAR} are the two scaling parameters which are derived from long ASAR backscatter time series using the methods described in Wagner et al. (2008).

Tests with the disaggregated ASCAT-ASAR product show that it compares equally well to in-situ measurements as the 25km ASCAT product (Albergel et al., 2010) but, overall, the added value of this product is not yet very clear given that the downscaling parameters are static, i.e. all information about the temporal behavior still comes from the original 25 km ASCAT soil moisture product (Matgen et al., 2012). Nevertheless, the product facilitates data handling and interpretation of the soil moisture information at much finer scales (through its advisory flags), making it thus a valuable product from a

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practical point of view (Wagner et al., 2013). This is likewise true for the ECMWF-ASAR product which is shown in the following section.

4 Results

For the verification of the forecast quality, weekly mean values have been calculated both for COSMOS measurements and seasonal soil moisture forecasts. Each ensemble member has been averaged separately. This approach was chosen for two reasons: First, possible outliers and unpredictable scales in space and time are smoothened out due to this procedure. Second, it is mainly the trend which is of interest while daily values of seasonal forecasts should not be used anyway (Molteni et al., 2011). However, anomalous weather events can also be suppressed with this averaging (ECMWF, 2013b).

To calculate statistical measures, the mean of the weekly values has been used for each of the seven seasonal forecasting runs investigated (October 2011 to April 2012). The root mean squared error (RMSE; Wilks, 2006) and the Pearson coefficient of linear correlation (PCC; Wilks, 2006) have been chosen as statistical indices. Figure 2 shows the results for the seasonal forecast of February 2012 validated at the station KLEE. The forecasting period is characterized by very dry soils at the beginning of the period followed by the rainy season starting in April. During the wet season, the spread of measurements within a week is clearly higher than during dry periods. In the forecasting plots (Fig. 2b–f), the weekly mean value of the COSMOS station is marked with black dots.

The IFS reference forecast ("IFS", Fig. 2b) shows the typical behavior of the model soil as H-TESSEL is not able to reproduce very dry soils (Balsamo et al., 2009). So during the dry season the soil moisture content is overestimated in the reference ensemble, and as a consequence, the seasonal cycle is not pronounced enough. This leads to high values in RMSE (33.1), so the climatology is not appropriate for forecast purposes in this case. Due to the CDF matching ("IFS CDF", Fig. 2c), the tracing of the

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seasonal cycle can be improved, but still soils are too wet in the model. Though the spread is increased due to the CDF matching, the very dry soils are still not captured by the model. Both RMSE and PCC are improved compared to the original data set.

The ensemble forecast of 1 February 2012 ("EPS", Fig. 2d) has the same problem as the reference forecast. The soil is too wet during the dry season, and the seasonal cycle of soil moisture is not captured well, resulting in a low PCC (0.43) and a high RMSE (24.6). CDF matching to the ASCAT climatology is improving the forecast ("EPS CDF", Fig. 2e). Again, the spread is increased and the seasonal cycle better fits the measurements. RMSE (17.3) is clearly improved compared to the raw EPS forecast. Downscaling to 1 km further improves the forecast ("EPS CDF1", Fig. 2f) for this case. The largest differences between model and station measurement are during the transition period from dry to wet season (starting around week +9 in this year), where also the spread in the model is highest. The dry soil at the beginning of the forecasting period is captured much better after this two-step correction, while the good forecast quality for months six and seven is still kept after this procedure. Both RMSE (14.2) and PCC (0.71) can be significantly improved compared to the original EPS.

The averaged results for all seven seasonal forecasts can be seen in Fig. 3. In terms of the grid box size of the seasonal forecasting model, both stations are situated close together. Nevertheless, the forecast quality is clearly different for KLEE and Mpala-North. Concerning the PCC, CDF matching and downscaling is improving the score for Mpala-North and the EPS is better than the reference ensemble, but all of the differences are non-significant (significance was checked with the Wilcoxon-Mann-Whitney test available in the statistical program R). For KLEE, the seasonal cycle of the station is better represented by the climatology, thus leading to higher PCC, but the total soil moisture amounts are strongly overestimated. For the seasonal forecast, the calibration and downscaling is improving the PCC, but again, the results are not significant.

For the RMSE, the climatology is hard to beat at Mpala-North and the original seasonal forecast is worse than the reference forecast (not significant). CDF matching is improving forecasting quality highly significantly both for climatology and seasonal

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forecast. This calibration works better for EPS, so it has little forecast skill compared to the reference. The downscaling is degrading the forecast quality a little bit (not significantly), which might be caused by a problem in the representativeness of the soil type in the model. For KLEE, the RMSE can be decreased highly significantly with CDF matching and also the downscaling is highly significantly better than the simple CDF matched forecast on average. For this station, the seasonal forecast has a positive forecast skill both for original and calibrated forecasts.

5 Conclusions and outlook

It can be concluded that the proposed calibration and downscaling approach is working and provides useful results. This is demonstrated for two stations in Kenya. The seasonal forecasting system (and also the reference ensemble made out of high-resolution historical forecasts) has known problems in representing dry soils, thus leading to an unrealistic seasonal cycle. Using the information contained in ASCAT soil moisture time series, the described weakness can be partially overcome when calibrating the model forecasts. This CDF matching is working well even though the soil layers which are compared are of different thickness (ASCAT: 1–2 cm, ECMWF: 28 cm) and has major advantages over a calibration based on station measurements, as ASCAT satellite soil moisture is available in sufficient quality almost everywhere over land (except rain forests, deserts and polar regions). Furthermore, this approach is computationally simple. Nevertheless, the polynomials have to be recalculated if changes in the model physics or the satellite retrieval algorithm are taking place. The downscaling to a 1 km grid with the ASCAT-ENVISAT ASAR relation is also working in principle, but the results are not as clear as for the CDF matching. This might be due to problems in the representativeness of the soil properties used in the model soil or small scale features at the measurement site not resolvable with this approach.

An application for this approach might be in the early warning of threats to food security in dry regions around the world, especially in combination with crop models.

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Moreover it is relevant to monitor soil moisture forecasts to detect weaknesses in forecast quality, as this parameter is still not well captured by weather forecasting models nowadays though it is a relevant one especially for convective processes.

In a next step, it is planned to test the approach for other climate regions and more seasonal forecast runs. Especially for dry climates, it would be interesting to combine the seasonal soil moisture forecasts with drought indices. Furthermore, the variability on the 1 km grid should be investigated in detail for further improvement of this promising method.

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References

Albergel, C., Calvet, J.-C., de Rosnay, P., Balsamo, G., Wagner, W., Hasenauer, S., Naeimi, V., Martin, E., Bazile, E., Bouyssel, F., and Mahfouf, J.-F.: Cross-evaluation of modelled and remotely sensed surface soil moisture with in situ data in southwestern France, Hydrol. Earth Syst. Sci., 14, 2177–2191, doi:10.5194/hess-14-2177-2010, 2010.

Balsamo, A., Viterbo, P., Beljaars, A., van den Hurk, B., Hirschi, M., Betts, A. K., and Scipal, K.: Revised Hydrology for the ECMWF Model: Verification from Field Site to Terrestrial Water Storage and Impact in the Integrated Forecast System, J. Hydrometeorol., 10, 623–643, 2009.

Balsamo, G., Pappenberger, F., Dutra, E., Viterbo, P., and van den Hurk, B.: A revised land hydrology in the ECMWF model: a step towards daily water flux prediction in a fully-closed water cycle, Hydrol. Process., 25, 1046–1054, doi:10.1002/hyp.7808, 2011.

Das, N. N., Entekhabi, D., and Njoku, E. G.: An algorithm for merging SMAP radiometer and radar data for high-resolution soil-moisture retrieval, IEEE T. Geosci. Remote, 49, 1504–1512, 2011.

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Dharssi, I., Bovis, K. J., Macpherson, B., and Jones, C. P.: Operational assimilation of ASCAT surface soil wetness at the Met Office, Hydrol. Earth Syst. Sci., 15, 2729–2746, doi:10.5194/hess-15-2729-2011, 2011.

Dorigo, W. A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Xaver, A., Gruber, A., Drusch, M., Mecklenburg, S., van Oevelen, P., Robock, A., and Jackson, T.: The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements, Hydrol. Earth Syst. Sci., 15, 1675–1698, doi:10.5194/hess-15-1675-2011, 2011.

Drusch, M. and Viterbo, P.: Assimilation of screen-level variables in ECMWF Integrated Forecast System: A study on the impact on the forecast quality and analyzed soil moisture, Mon. Weather Rev., 135, 300–314, 2007.

ECMWF: MARS User Guide, ECMWF Technical Notes, January 2013, 55 pp., 2013a.

ECMWF: User Guide to ECMWF forecast products, Version 1.1, July 2013, 129 pp., available at: http://www.ecmwf.int/products/forecasts/guide/index.html (last access: 13 November 2013), 2013b.

Ferranti, L. and Viterbo, P.: The European Summer of 2003: Sensitivity to Soil Water Initial Conditions, J. Climate, 19, 3659–3680, 2006.

Matgen, P., Fenicia, F., Heitz, S., Plaza, D., De Keyser, R., Pauwels, V. R. N., Wagner, W., and Savenije, H.: Can ASCAT-derived soil wetness indices reduce predictive uncertainty in well-gauged areas? A comparison with in situ observed soil moisture in an assimilation application, Adv. Water Resour., 44, 49–65, 2012.

Molteni, F., Stockdale, T., Balmaseda, M., Balsamo, G., Buizza, R., Ferranti, L., Magnusson, L., Mogensen, K., Palmer, T., and Vitard, F.: The new ECMWF seasonal forecasting system (System 4), ECMWF Technical Memorandum (Technical Report) No. 656, 49 pp., 2011.

Reichle, R. H. and Koster, R. D.: Bias reduction in short records of satellite soil moisture, Geophys. Res. Lett., 31, L19501, doi:10:1029/2004GL20938, 2004.

Scipal, K.: Definition of Quality Flags, ASCAT Soil Moisture Report Series, 7, Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Austria, 2005.

Shepard, D.: A two-dimensional interpolation function for irregularly spaced data, Proc. 23rd ACM Nat.Conf., Brandon/Systems Press, Princeton, NJ: 517–524, 1968.

Vachaud, G., Passerat de Silans, A., Balabanis, P., and Vauclin, M.: Temporal stability of spatially measured soil water probability density function, Soil Sci. Soc. Ame., 49, 822–828, 1985.

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Wagner, W., Blöschl, G., Pampaloni, P., Calvet, J.-C., Bizzarri, B., Wigneron, J.-P., and Kerr, Y.: Operational readiness of microwave remote sensing of soil moisture for hydrologic applications, Nord. Hydrol., 38, 1–20, 2007.
Wagner, W., Pathe, C., Doubkova, M., Sabel, D., Bartsch, A., Hasenauer, S., Blöschl, G., Scipal, K., Martinez-Fernandez, J., and Löw, A.: Temporal stability of soil moisture and radar backscatter observed by the Advanced Synthetic Aperture Radar (ASAR), Sensors, 8, 1174–1197, 2008.
Wagner, W., Bartalis, Z., Naeimi, V., Park, S.-E. , Figa-Saldana, J., and Bonekamp, H.: Status of the METOP ASCAT soil moisture product, in: IEEE Geoscience and Remote Sensing Symposium (IGARSS'2010), doi:10.1109/IGARSS.2010.5649298, Honolulu, USA, 276–279, 2010.
Wagner, W., Hahn, S., Kidd, R., Melzer, T., Bartalis, Z., Hasenauer, S., Figa, J., de Rosnay, P., Jann, A., Schneider, S., Komma, J., Kubu, G., Brugger, K., Aubrecht, C., Züger, J., Gangkofner, U., Kienberger, S., Brocca, L., Wang, Y., Blöschl, G., Eitzinger, J., Steinnocher, K., Zeil, P., and Rubel, F.: The ASCAT Soil Moisture Product: A Review of its Specifications, Validation Results, and Emerging Applications, Meteorol. Z., 22, 5–33, 2013.
Western, A. W., Grayson, R. B., Blöschl, G., Willgoose, G. R., and McMahon, T. A.: Observed spatial organization of soil moisture and its relation to terrain indices, Water Resour. Res., 35, 797–810, doi:10.1029/1998WR900065, 1999.
Wilks, D. S.: Statistical Methods in the Atmospheric Sciences, 2nd Edn., International Geophysics Series, 91, Academic Press, 2006.
Zreda, M., Shuttleworth, W. J., Zeng, X., Zweck, C., Desilets, D., Franz, T., and Rosolem, R.: COSMOS: the COsmic-ray Soil Moisture Observing System, Hydrol. Earth Syst. Sci., 16, 4079–4099, doi:10.5194/hess-16-4079-2012, 2012.

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Fig. 1. Location of the COSMOS in situ soil moisture measurements sites Mpala-North (M) and KLEE (K) (picture from http://cosmos.hwr.arizona.edu).

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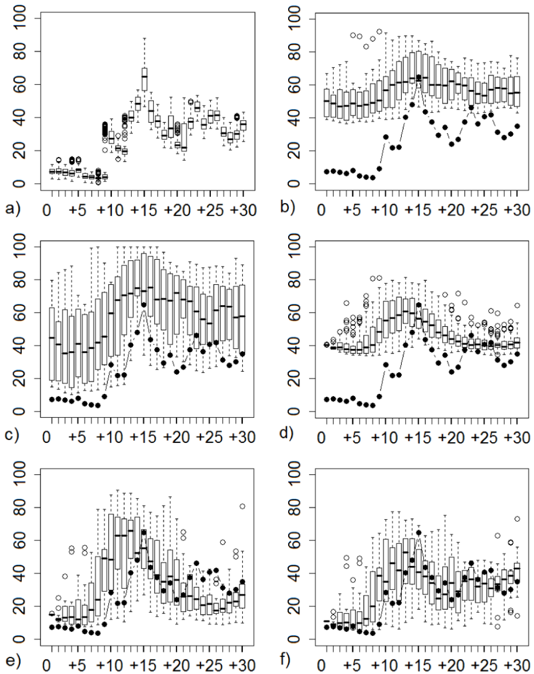

Fig. 2. COSMOS soil moisture measurements **(a)** and forecasts **(b–f)** for the period February to August 2012 for the station KLEE in Kenya. Numbers on the abscissa indicate the number of weeks since 1 February 2012 and numbers on the ordinate indicate soil moisture index in %. For the measurements **(a)**, each boxplot contains 168 values (24 hourly values × 7 days). For the forecasts, one column is representing all ensemble members, whereas the forecasts of one week (one forecasted value every day) are averaged for each member separately. **(b)** is the IFS reference climatology, **(c)** the CDF matched IFS reference climatology, **(d)** is the EPS ensemble forecast, **(e)** is the CDF matched EPS ensemble forecast and **(f)** is the CDF matched and downscaled EPS ensemble forecast. Black dots in **(b–f)** are the mean values of the COSMOS station for the forecasting period.

	KLEE				MPALA			
	IFS CDF	EPS	EPS CDF	EPS CDF 1	IFS CDF	EPS	EPS CDF	EPS CDF 1
RMSE								
IFS	⮝	▲	▲	▲	▲	↓	▲	↑
IFS CDF		▲	▲	▲		▼	↑	↓
EPS			↑	▲			▲	▲
EPS CDF				▲				↓
PCC								
IFS	↓	▼	▼	⮟	↓	↓	↑	↑
IFS CDF		▼	▼	⮟		↑	↑	↑
EPS			↑	↑			↑	↑
EPS CDF				↑				↑

Fig. 3. Quality of the forecast expressed in RMSE (top block) and PCC (bottom block) for stations KLEE (left) and Mpala-North (right). The arrow in a box is pointing upwards if the forecast (top row) is better than the forecast (left column) on average for the 7 forecasting runs. "↑" means that the improvement is not significant, "⮝" significant (75–89.9) and "▲" highly significant (90–100).