Downscaling of seasonal soil moisture forecasts using satellite data

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Abstract

A new approach to downscale soil moisture forecasts from the seasonal ensemble prediction forecasting system of ECMWF (European Centre for Medium-Range Weather Forecasts) 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 and the low spatial resolution of the seasonal forecasts are the main reason why soil water information is hardly used so far. The basic idea to overcome some of these problems is the application of additional information provided by two satellite sensors (ASCAT and ENVISAT ASAR) to improve the forecast quality, mainly to reduce model bias and increase the spatial resolution. Seasonal forecasts from 2011 and 2012 have been compared to in-situ measurements sites in Kenya to test this two-step approach. Results confirm that this downscaling is adding skill to the seasonal 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 both difficult to measure and forecast. 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 can hardly be captured by point measurements. Nevertheless, ground-based methods can be applied over any depth, accurately calibrated, and logged at any time scale (Western et al., 2002). Many of the globally available ground-based soil moisture measurements are thus collected, harmonized, and made available to users through the ISMN (International Soil Moisture Network; http://ismn.geo.tuwien.ac.at; Dorigo et al., 2013). Remote sensing, on the other hand, provides excellent spatial coverage over large areas and spatial representativeness, but the shallow measurement depth, confounding influence of vegetation, indirect nature of the method, and relatively infrequent repeat cycles hamper the use of the data (Western et al., 2002).

Due to the processes described above, the need for proper soil moisture characterisation 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). Furthermore, deficits in the short-range precipitation forecasts and representation of the seasonal vegetation cycle (Balsamo et al., 2009) are intensifying the forecasting problems. Thus, (seasonal) soil moisture forecasts are hardly 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 improve forecast representativeness and accuracy, a new method to downscale seasonal soil moisture forecasts of the ECMWF ensemble forecasting system, providing high-resolution soil water forecasts, is presented in this paper.

Data sources used for the investigation are described in section 2. Section 3 includes the calibration and downscaling approach, and in section 4 the results are presented. Conclusions are drawn in section 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 ECMWF. Soil moisture measurements are available from satellite platforms and in-situ measurement sites in the testing region, located in Kenya. In the following subsections, the data sources are described in detail.

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 hours after sensing) ASCAT surface soil moisture maps at 25 km and 50 km spatial scale are available operationally since December 2008 (Wagner et al., 2010). ASCAT data used for this study have been provided by Vienna Technical University. The backscattered measurements are used to estimate the surface soil moisture content (Wagner et al., 2013; their Eq. 1), which is a number ranging between 0 (dry limit) and 1 (moist limit), usually expressed in %. To convert it to volumetric soil moisture content (being comparable to ECMWF model output), the soil porosity is necessary (Wagner et al., 2013; their Eq. 2). There are no reliable porosity data for the target region in Kenya, so this conversion is not possible without introducing an additional error source, thus model output and COSMOS (COsmic-ray Soil Moisture Observing System) measurements are converted to the index with values between 0 and 100% to make all data sets comparable. ASCAT data are stored as time series for single grid points, so 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 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° and 91 vertical levels with a model top at ~0.01hPa. Soil processes are modeled by H-TESSEL (Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land; Balsamo et al., 2009; Balsamo et al., 2011). Data output for soil moisture is provided daily for 4 vertical soil levels: 0-7cm, 7-28cm, 28-100cm, 100-289cm. The seasonal forecasts include 51 ensemble members. Forecast runs are started at 00 UTC on the 1st of each calendar month with a lead time of 215 days (5160 hours). Data have been extracted from the Meteorological Archival and Retrieval System (ECMWF, 2013a) for 4x4 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^3m^{-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

$$SWI = \left(\frac{0.25 SWL_1 + 0.75 SWL_2}{SWL_{SAT}} \right) \cdot 100 , \quad (1)$$

where SWL_{SAT} [m^3m^{-3}] is the saturation value for the grid point (solely depending on the soil type); SWL_i [m^3m^{-3}] is the forecasted volumetric soil water of the i^{th} 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 find out if the seasonal forecasting system has a prediction skill higher than a climatological forecast. Soil moisture data from 00UTC 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, the IFS grid points with locations corresponding to the 16 EPS 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.

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. 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). Fig. 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 15-30cm (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 (0-7cm) and layer 2 (7-28cm) data calculated in Equation (1). COSMOS stations are measuring average soil water content within a diameter of a few hectometers (Zreda et al., 2012). The correction to atmospheric water vapor content described by Rosolem et al. (2013) has been applied to the COSMOS level-3 (Zreda et al., 2012) soil moisture data, which are provided in volumetric soil moisture [m^3m^{-3}]. Afterwards 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). Unfortunately, no other in-situ measurement sites are available within Eastern Africa where the satellite downscaling parameters (see chapter 3) have been available for this investigation.

3 The calibration and downscaling approach

To downscale seasonal soil moisture forecasts from the global grid to a 1km resolution with satellite data, 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 a 1km 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 October 1st, 2011 to April 1st, 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 25km ASCAT soil moisture data, ASAR (Advanced Synthetic Aperture Radar) 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 as they are often influenced by the same parameters (e.g. precipitation). 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 25km ASCAT soil moisture data,

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

is used (Wagner et al., 2013).

m_s^{1km} is the estimated surface soil moisture content over the 1km area centered at the coordinates (x, y). m_s^{25km} is the calibrated ECMWF soil moisture at forecasting time t. Originally, m_s^{25km} 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). So far, the coefficients have been available solely for Europe and Australia. For the investigation described herein, they have been calculated for Eastern Africa, too.

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 practical point of view (Wagner et al., 2013). This is likewise true for the ECMWF-ASAR product which is shown in the following section. Comparing the measurements at station KLEE (36.7 on average) with the closest ASCAT grid point (50.8) and the downscaled ASCAT soil moisture data at the four 1km grid points surrounding the in-situ station (50.3, 50.7, 50.0, 51.6) shows that the downscaling changes the ASCAT measurements just slightly, improving 3 out of 4.

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.

Fig. 2 shows the results for the seasonal forecast of February 2012 validated at the station KLEE. The forecasting period is characterized by 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-2g), the weekly mean value of the COSMOS station is marked with black dots.

The IFS climatological reference forecast (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 (24.1), so the climatology is not appropriate for forecast purposes in this case.

Due to the CDF matching (Fig. 2c) and downscaling (Fig. 2d), the tracing of the seasonal cycle can be improved, but still soils are too wet in the model on average. Though the spread is increased mainly due to the CDF matching, moisture is still overestimated by the model for periods with dry soils. Both RMSE and PCC are improved after the downscaling.

The ensemble forecast of February 1st, 2012 (Fig. 2e) has the same problem as the reference forecast with the soil being too wet during the dry season. The seasonal cycle of soil moisture is captured much better in this case, resulting in a low RMSE (12.7) but also a low PCC (0.31). CDF matching to the ASCAT climatology is improving the forecast (Fig. 2f), though soil moisture is even underestimated at the beginning of the forecasting period. Due to this underestimation, RMSE (12.9) is slightly worse compared to the raw EPS forecast, but the seasonal cycle better fits the measurements (PCC=0.46). Downscaling to 1km improves the forecast (Fig. 2g) for this case. The dry soil at the beginning of the forecasting period is still underestimated, but the wet season is predicted much better with the downscaled forecast product. The good forecast quality for months six and seven is still kept after this procedure. Both RMSE (8.1) and PCC (0.73) can be clearly improved compared to the original EPS.

So it can be summarized for this example that both for the climatological forecast and the seasonal forecast the downscaling approach improves the forecast quality.

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 slightly different for KLEE and Mpala-North. Concerning the PCC, downscaling is improving the score for Mpala-North both for climatology and EPS forecasts. For the latter, the improvement (from 0.40 to 0.58) is significant. Significance was tested with the Wilcoxon-Mann-Whitney test available in the statistical program R. Furthermore, the EPS is better on average than the reference ensemble, but not significant (0.44 vs. 0.40). As shown in Fig.2 for one case, the seasonal cycle is represented well by the climatology for station KLEE, but with a large wet bias. Due to this, PCC for the climatology is highly significant better at KLEE as the bias is neglected for computing the correlation. The downscaling is improving PCC compared to the original grid both for climatology and EPS on average, but not significant.

For the RMSE, the positive impact of the downscaling approach is even clearer. Climatology is hard to beat at Mpala-North and the original seasonal forecast is significantly worse on average than the reference forecast, but for both systems, the downscaled product is highly significant better, reducing RMSE from 22.9 to 12.7 (for climatology) and from 26.2 to 19.1 (for seasonal EPS). This is also true for KLEE, whereas the EPS outperforms the reference climatology for this station. RMSE can be highly significant reduced due to the downscaling from 24.5 to 22.2 (for climatology) and from 15.6 to 11.9 (for seasonal EPS).

5 Conclusions and outlook

It can be concluded that the proposed downscaling approach with the included calibration 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: 1-2cm, ECMWF: 28cm), 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 1km grid with the ASCAT-ENVISAT ASAR relation is also working well. Statistics is showing that the downscaling is improving both climatology and seasonal forecasts, whereas results are highly significant for RMSE. Concerning the forecast quality of the model, it can be stated that the climatology created out of high-resolution analyses is an ambitious benchmark for the seasonal forecast performance.

An application for this approach might be in the early warning of threats to food security in dry regions around the world, thus this approach has been tested in Eastern Africa though the data coverage of in-situ measurements is poor in this region. It would be especially interesting to use the downscaled products in combination with crop models. 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 1km grid should be investigated in detail for further improvement of this promising method.

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Figure 1. Location of the COSMOS in situ soil moisture measurements sites Mpala-North (M) and KLEE (K)~~.~~ (Picture from Google maps).

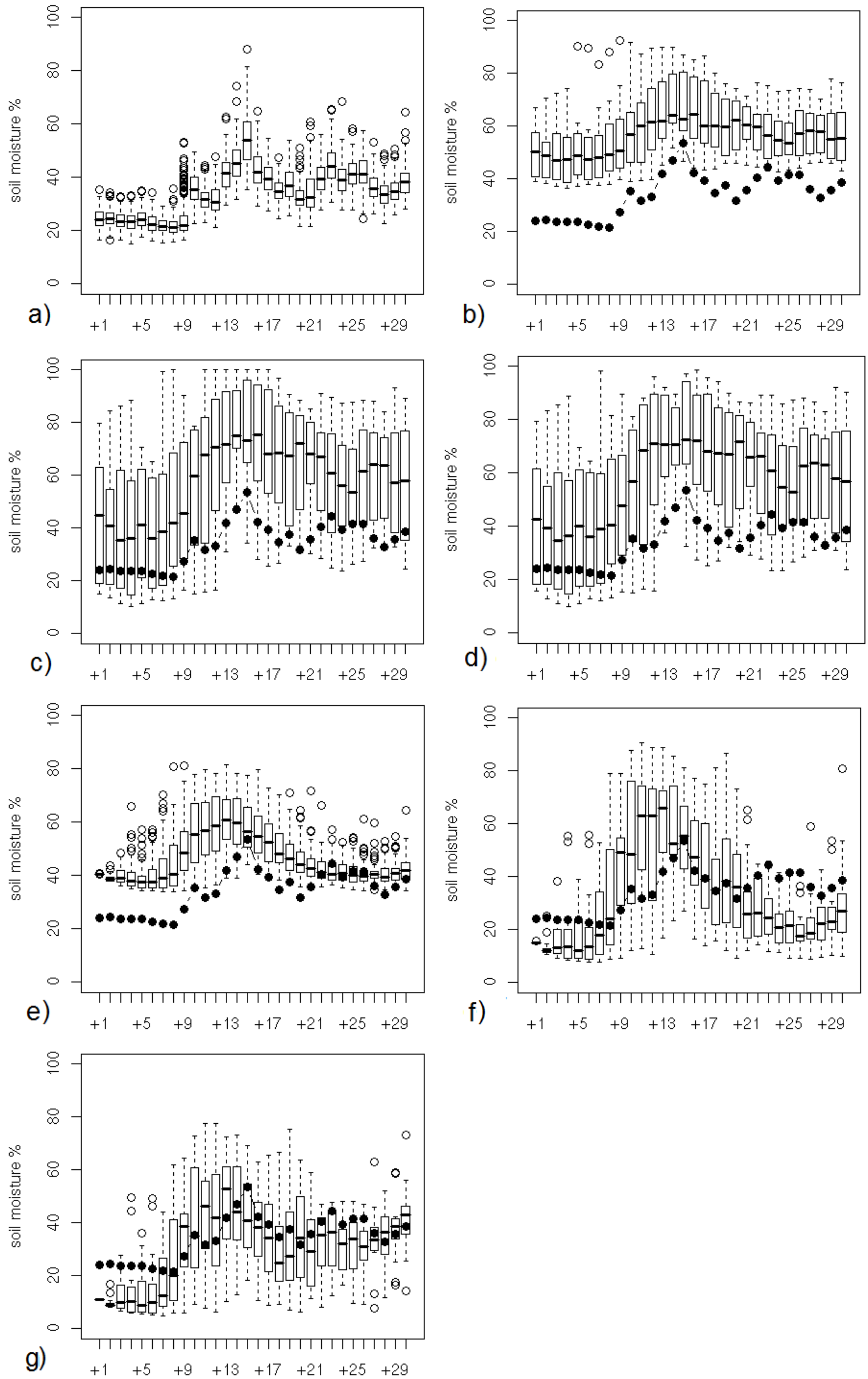
a)
b)
c)
d)
e)
f)
g)
soil moisture %
0
20
40
60
80
100
+1
+5
+9
+13
+17
+21
+25
+29

Figure 2. COSMOS soil moisture measurements (a) and forecasts (b-h) for the period February to August 2012 for the station KLEE in Kenya. Numbers on the abscissa indicate the number of weeks since February 1st, 2012. 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) the CDF matched and downscaled IFS reference climatology, e) is the EPS ensemble forecast, f) is the CDF matched EPS ensemble forecast and g) is the CDF matched and downscaled EPS ensemble forecast. Black dots in b)-g) are the mean values of the COSMOS station for the forecasting period.

	KLEE					MPALA				
	IFS CDF	IFS CDF 1	EPS	EPS CDF	EPS CDF 1	IFS CDF	IFS CDF 1	EPS	EPS CDF	EPS CDF 1
RMSE										
IFS	▲	▲	▲	▲	▲	▲	▲	⌄	▲	↑
IFS CDF		↑	▲	⌃	▲		↑	▼	↓	▼
IFS CDF 1			▲	⌃	▲			▼	↓	▼
EPS				↓	▲				▲	▲
EPS CDF					▲					▼
PCC										
IFS	↓	↑	▼	▼	⌄	↓	↑	↓	↑	↑
IFS CDF		↑	▼	▼	⌄		↑	↑	⌃	↑
IFS CDF 1			▼	▼	▼			↓	↑	↑
EPS				↑	↑				↑	⌃
EPS CDF					↑					↑

Figure 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). IFS (EPS) is the reference climatology (seasonal forecast), IFS (EPS) CDF is the bias corrected one and IFS (EPS) CDF 1 is the bias corrected and downscaled climatology (forecast).