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Impact of improved soil moisture on the ECMWF precipitation forecast in West Africa

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Abstract

West Africa is a region of strong coupling between soil moisture and precipitation and where numerical weather precipitation generally exhibits poor skills. This region has been the focus of the African Monsoon Multidisciplinary Analysis - Land-surface Model Intercomparison Project (AMMA-ALMIP) in which the European Medium-Range Weather Forecasts (ECMWF) land surface scheme (HTESSEL)– among others – has been driven offline by accurate meteorological forcing in order to produce improved soil moisture estimates. This paper examines the impact of an improved initial condition for soil moisture from the HTESSEL ALMIP run on West Africa short-range precipitation forecasts with the ECMWF Integrated Forecast System (IFS). A set of forecasts covering the month of August 2006 is initialized with the soil moisture from ALMIP and compared with the operational setup. The mean difference in the soil moisture at the initial time is mirrored by differences in the evaporation and convective available potential energy in the second day of forecasts. However, it is shown that while direct and beneficial impact of a more realistic soil moisture is obtained for accumulated precipitation in the regions over the coast of the Gulf of Guinea and eastern Sahel, over the rest of the Sahel the impact is detrimental or neutral. An argument is made that the presence of convective inhibition and more complex non-local feedbacks, such as moisture convergence associated with the monsoon flow, play a more important role than the soil moisture–precipitation coupling over those regions.

1 Introduction

During the West African wet monsoon season (July-Sep) the main precipitation band associated with the Inter-Tropical Convergence Zone (ITCZ) moves northwards providing most of the Sahel annual rainfall. The Sahel [12^oN-18^oN] lies in the semi-arid region between the tropical humid zone near the Guinea coast and the Sahara desert and it is characterized by a strong north-south gradient in precipitation.

It has been shown that global Numerical Weather Prediction (NWP) models have difficulties in forecasting precipitation over the Sahel during the wet season of the West African monsoon (*Nuret et al.*, 2008). In particular, the European Centre for Medium-range Weather Forecasts (ECMWF) short-range forecast places the zonal mean rain band too far south with a lack of precipitation in the northern Sahel (*Agustí-Panareda and Beljaars*, 2008). This lack of precipitation is improved by correcting a dry bias associated with humidity from radiosondes used in the analysis (*Agustí-Panareda et al.*, 2009). This correction is also implemented in the special ECMWF reanalysis (*Agustí-Panareda and Beljaars*, 2008) covering the 2006 wet monsoon season and using the radiosonde and dropsondes data from the African Monsoon Multidisciplinary Analysis (AMMA) field experiment (see *Redelsperger et al.*, 2006). However, the ECMWF AMMA reanalysis still underestimates precipitation over Sahel.

The aim of this paper is to investigate the impact of soil moisture on the mean precipitation forecast during the West African monsoon season. Soil moisture is known to play an important role in the hydrological cycle over semi-arid regions, in particular the Sahel (*Koster et al.*, 2004). Over Sahel, the feedback between soil moisture and precipitation can be positive or negative depending on whether the convective system is at incipient or mature stage (e.g. *Gantner and Kalthoff*, 2009). Mature and organized large convective systems have a positive feedback with soil moisture because they are sensitive to convective available potential energy (CAPE) which is higher on wet soils. On the other hand, the initiation of moist convection has been shown to have a negative feedback with soil moisture (e.g. *Taylor and Ellis*, 2006; *Gantner and Kalthoff*, 2009). This is because the triggering of convection involves the removal of convective inhibition (CIN) by vigorous thermals. Thus, convective triggering is favoured by drier soils in the vicinity of wet patches, through the creation of a mesoscale circulation across the soil moisture gradient resulting in low-level moisture convergence and higher sensible heat flux (e.g. *Taylor et al.*, 2007, 2009).

In the ECMWF Integrated Forecast System (IFS) model cycle CY32r3, soil moisture is initialized by using the short-range forecast field adjusted by a simple Optimal Interpolation scheme (*Mahfouf et al.*, 2000) in the surface analysis to reduce departures in 2m temperature and 2m relative humidity between the forecast and observations. The soil moisture evolution is largely determined by precipitation and evaporation (including evapotranspiration). Moreover, the soil moisture adjustments from the surface analysis are limited by the availability of SYNOP observations and by the meteorological conditions at the time of the analysis. Thus, it is not surprising that the model soil moisture can accumulate large errors.

In order to investigate the impact of soil moisture on precipitation, forecast experiments with “more realistic” soil moisture initial conditions have been performed. Such soil moisture fields have been produced by running the ECMWF land-surface model HTESSEL (*Balsamo et al.*, 2009) offline for the month of August 2006 using satellite-derived precipitation, radiation forcing and ECMWF atmospheric analyses as part of the AMMA Land-surface Model Intercomparison Project (ALMIP, see *Boone et al.*, 2009). The idea is that a land surface model will produce a more accurate soil moisture state if it is forced with more accurate precipitation and radiation fields. The resulting soil moisture fields over the AMMA region are used to initialize a set of 5-day forecasts with the IFS model. Note that longer forecast ranges will be affected by the model precipitation northward drift (*Agustí-Panareda and Beljaars*, 2008) and boundary layer recovery time over wet patches produced by mesoscale convective systems is of the order of two days (*Gantner and Kalthoff*, 2009).

The experiment is performed for the whole month of August 2006 when the AMMA field experiment deployed up to 8 radiosoundings per day in several sites in West Africa which were used in the AMMA reanalysis (*Agustí-Panareda and Beljaars*, 2008). The experiment uses the AMMA reanalysis as atmospheric initial conditions. The standard forecast from the AMMA reanalysis is also used as a control experiment. The only difference between the two experiments (referred to as EXP and CONTROL) is the initial soil moisture field over the AMMA region.

Figure 1 shows the mean difference in the soil moisture initial conditions between the two experiments (EXP-CONTROL) and illustrates the shortcomings in the soil moisture from the AMMA reanalysis by considering CONTROL-EXP. It is clear that there is a deficit of soil moisture within the latitude band between 15^{o}N and 20^{o}N and also in the eastern part of the Sahel, particularly east and south of lake Chad (around 13^{o}N, 15^{o}E). These are the regions where the model is known to have a lack of precipitation. In the tropical region, within 5 degrees from the coast, the model precipitation is too high and so is the soil moisture in the AMMA reanalysis. Finally, there are parts of the Sahel where the soil moisture is too high in the AMMA reanalysis despite the lack of precipitation in the ECMWF IFS model. These are regions where there are SYNOP stations and the surface analysis is producing increments of soil moisture to compensate for the 2m temperature being too high and/or 2m humidity being too low in the model background.

The differences in soil moisture clearly point out the influence of precipitation forecast deficiencies on soil moisture deficiencies in the model. The following section addresses the question of whether a more realistic soil moisture will have any significant improvement on the forecast of precipitation.

2 Results

The impact of the more realistic soil moisture on the short-range forecast is shown in Figs 2a, 2b and 2c. During the second day of forecast, an increase/decrease in evaporation occurs over the regions where there is an increase/decrease in soil moisture. Evaporation decreases south of 15^{o}N between 17^{o}W - 15^{o}E and it increases north of 15^{o}N and to the east of 15^{o}E and north of 10^{o}N.

The increase in evaporation is also linked to an increase in Convective Available Potential Energy (CAPE) north of 15^{o}N (up to $\sim$ 400 J kg^{-1}) and east of 15^{o}E with an increase of up to 900 J kg^{-1}. The Convective Inhibition (CIN) does not change significantly with the increase/decrease of soil moisture (not shown). These CAPE and CIN values are obtained by using the pseudo-adiabatic parcel ascent from the model level near the surface which produces maximum CAPE. Although CAPE values are much smaller on average near the coast, the feedback between changes in evaporation and CAPE is still relatively strong south of 10^{o}N. That is, the mean CAPE difference is between 100 and 300 J kg^{-1} in areas where mean CAPE is less than 500 J kg^{-1} (see Fig. 2d).

Mean changes in precipitation are consistent with changes in CAPE within the latitude band between 10^{o}N and 15^{o}N, where there is a mean increase of precipitation east of 17^{o}E of up to 2mm/day and a mean decrease to its west of up to 3 mm/day around the region of Bamako (12.32^{o}N, 7.57^{o}W). Note that over the region with precipitation increase there are large values of mean CAPE (between 2000 and 2500 J kg^{-1}) and low values of mean CIN (less than 20 J kg^{-1}) as shown in Fig. 2d. North of 16^o N, although there is an overall increase in CAPE, there is no change in precipitation. This is due to the fact that the model is not able to trigger deep convection in the northern Sahel region which is characterized by large amounts of mean CIN ($>$20 J kg^{-1} over the whole region and $>$50 J kg^{-1} west of Greenwich meridian). South of 10^{o}N, the precipitation decreases significantly in direct response to the decrease in evaporation and CAPE.

The total precipitation for day-2 forecast shows clearly that the main impact of using a more realistic soil moisture is to reduce the precipitation excess near the coast. As a result, the precipitation forecast in the coastal region (5^{o}N-7^o, 7^{o}W-3^{o}E) is closer to the satellite-derived precipitation from GPCP (see Figs. 2e and 2f). The precipitation in the region of the ITCZ (around 10^{o}N) is also reduced when using the ALMIP moisture. The final result is an ITCZ which is too far south and has too little precipitation.

The drift in the ITCZ position during the forecast evolution is also a well-known problem in the ECMWF IFS model (*Agustí-Panareda and Beljaars*, 2008). Figure 3a shows the variation of monthly zonal mean precipitation with latitude and forecast lead time compared to GPCP. The drift of the ITCZ is shown by the increase in precipitation amount between 9^{o}N and 14^{o}N. In EXP, the precipitation forecast is generally reduced at all latitudes for the different forecast lead times compared to the CONTROL. This reduction is more pronounced at day three than at day one, indicating that the drift of the ITCZ is slower than in the CONTROL, albeit by a small amount. This is clearly observed in Fig. 3b which shows that over the eastern part of the Sahel the drift along the forecast is consistently reduced (Fig. 3b). However, this is not the case for the central Sahel, where the decrease is the same for all forecast lead times (Fig. 3c).

3 Summary and discussion

In West Africa the feedback between soil moisture and precipitation is much stronger in the wet region near the coast than in the drier region of the Sahel. South of 10^oN the decrease in soil moisture causes a decrease in mean precipitation of up to 3 mm/day in the short-range forecast. This is a good result as the precipitation is too large over the coast compared to the satellite-derived precipitation from GPCP. *Koster et al.* (2004) also found that the main region with strong coupling of soil moisture and precipitation over west and central Africa is located south of 10^oN. Another region which also shows some coupling and positive feedback can be found towards the east of lake Chad. Although the resulting increase in precipitation over that region is smaller in magnitude, it still presents an improvement in the mean forecast. Both regions which show positive feedback are characterized by low values of CIN.

The feedback between soil moisture and precipitation is not visible north of 15^oN, where there are large values of CIN and the model has difficulty triggering deep convective events. This is consistent with the different feedback signs between soil moisture and precipitation found in the literature. *Hohenegger et al.* (2009) relate the negative feedback to the presence of a stable layer above the boundary layer and therefore CIN. In agreement with this argument, *Gantner and Kalthoff* (2009), *Taylor et al.* (2007) and *Taylor et al.* (2009) also associate positive and negative feedbacks with mature and incipient stages of convection respectively. *Van den Hurk and van Meijgaad* (2009) also found a lack of precipitation response to CAPE changes over Northern Sahel. Similar results where obtained by *Findell and Eltahir* (2003) over the monsoon region of the arid Southwest in continental United States, where CIN is also high due to the formation of a capping inversion.

Other reasons for the problem of deep convective triggering in the model over West Africa could be linked to problems in the representation of soil moisture patterns and mesoscale circulations associated with the previous passage of MCSs (e.g. *Gantner and Kalthoff*, 2009; *Taylor et al.*, 2009).

Using a more realistic soil moisture improves the problem of the ITCZ southward shift over the eastern part of the Sahel but not over the central part, where it also reduces the precipitation amount in the ITCZ band, degrading the short-range precipitation forecast. This last results suggest that more complex non-local feedback mechanisms are involved in the precipitation predictability over Sahel, e.g. the low-level moisture convergence associated with the monsoon flow.

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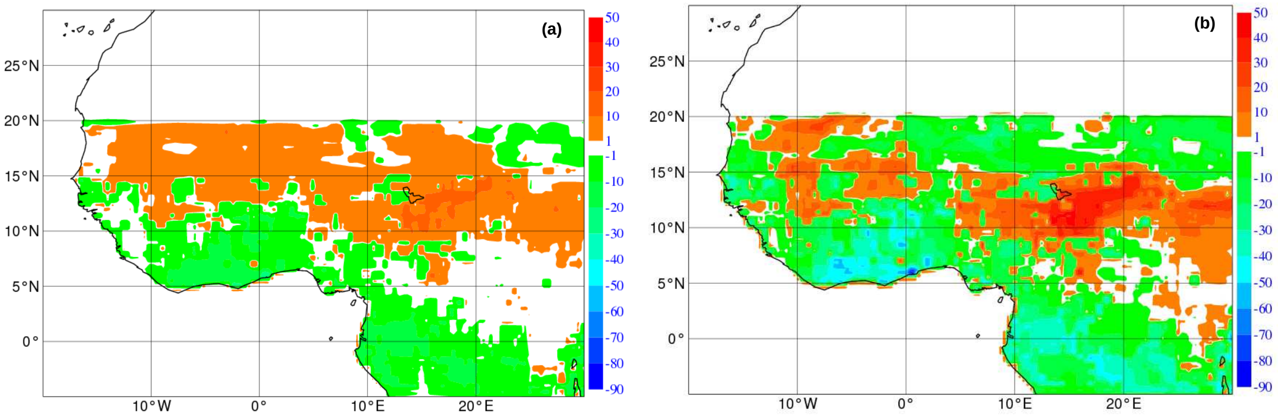

Figure 1: Mean difference in the initial soil moisture [units mm m^{-2}] in (a) the upper layer (0 to 7 cm deep) and (b) the second layer (7 to 28 cm deep) of the land-surface model between the experiment with ALMIP soil moisture and the control experiment for the period from 1 to 31 August 2006.

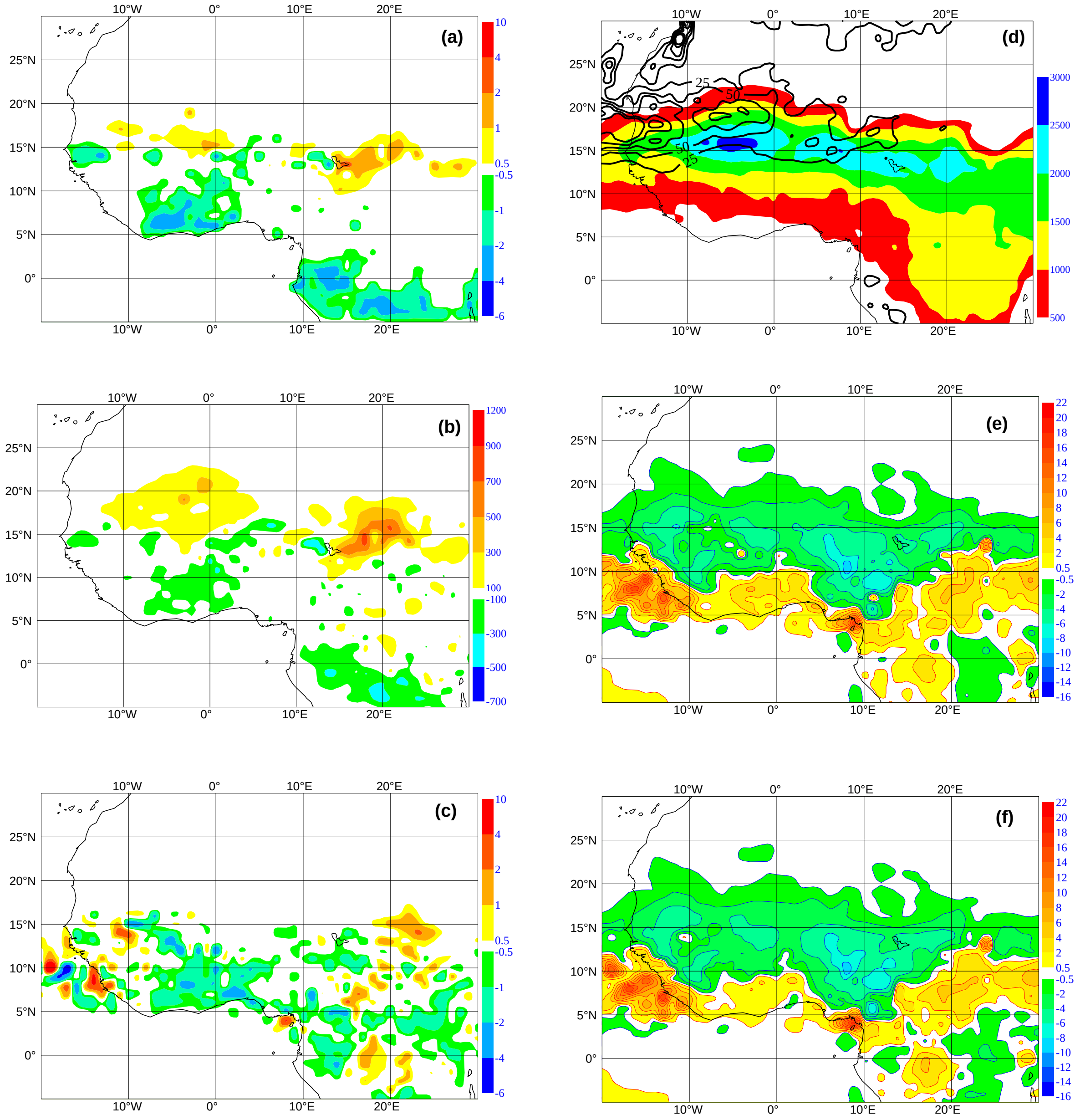

Figure 2: Left panels are monthly mean differences between the forecast initialized with ALMIP soil moisture and the control forecast (ALMIP - CONTROL) for: (a) evaporation [mm/day] from T+24 to T+48, (b) CAPE (J/m^2) at T+36, and (c) precipitation [mm/day] from T+24 to T+48; Right panels are mean fields of (d) CAPE [J/kg] (in colour) and CIN (contour lines, starting from 25 J/kg with contour interval of 25 J/kg) from the control forecast at T+36 and monthly mean error of precipitation forecast from T+24 to T+48 [mm/day] with respect to the Global Precipitation Climatology Project (GPCP) for (e) CONTROL-GPCP and (f) EXP-GPCP. The forecasts were initialized daily from 1 to 31 August 2006 at 00 UTC.

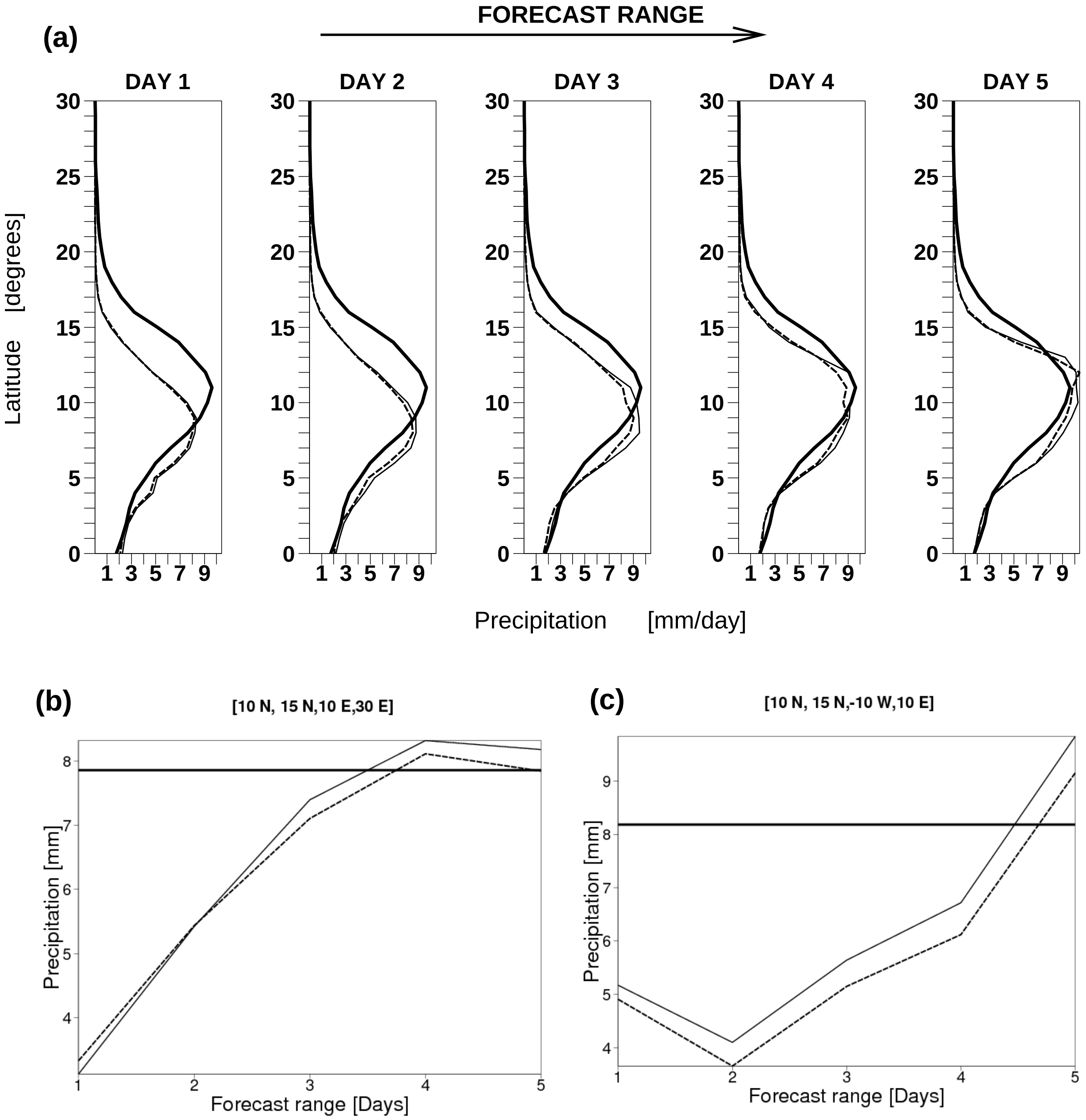

Figure 3: (a) Monthly mean zonally averaged precipitation with respect to latitude (y-axis) within the region 15^{o}W–30^{o}E and 0^{o}–30^{o}N for different forecast ranges. Bottom panels are monthly mean precipitation with respect to forecast range (x-axis) for the regions of (b) eastern Sahel (10^{o}E–30^{o}E, 10^{o}N–15^{o}N) and (c) central Sahel (10^{o}W–10^{o}E, 10^{o}N–15^{o}N). The lines for all plots correspond to the forecast initialized from ALMIP soil moisture (dash line), the control forecast (thin solid line) and the Global Precipitation Climatoloty Project (GPCP, thick solid line). The forecasts were initialized daily from 1 to 31 August 2006 at 00 UTC.