Diagnosing land-atmosphere interaction from a regional climate model simulation over West-Africa

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Version: 17 apr 2009

To be submitted for publication to J.Hydrometeorology

Keywords: Land-atmosphere interaction; Regional Climate Modeling; African hydrological cycle, recycling ratio, convective triggering potential
Abstract

Using a Regional Climate Model (RCM) covering a large area around the West African Sahel land-atmosphere interaction at climatological time scales has been explicitly explored using a range of diagnostics. First, areas and seasons of strong land-atmosphere interaction were diagnosed from the requirement of a combined significant correlation between soil moisture, evaporation and recycling ratio. The northern edge of the West African monsoon area during JJA, and an area just north of the equator (Central African Republic) during MAM were identified. Further analysis in these regions focused on the seasonal cycle of the Lifting Condensation Level (LCL) and the Convective Triggering Potential (CTP), and the sensitivity of CTP and near-surface dewpoint depressions ($H_{low}$) to anomalous soil moisture. From these analyses it is apparent that atmospheric mechanisms impose a strong constraint on the impact of soil moisture on the regional hydrological cycle.
Introduction

Land-atmosphere interaction is manifest at a wide range of spatial and temporal scales (Van den Hurk and Blyth, 2008). The planetary boundary layer is affected by the evaporation from the surface and changes in the atmospheric humidity affect surface evaporation within a couple of hours. The Lifting Condensation Level (LCL) is strongly coupled to the surface relative humidity and soil moisture (Betts, 2004). The ability of the atmosphere to produce precipitation is partly dependent on surface fluxes affecting convective activity and moisture supply at a similar time scale (Findell and Eltahir, 2003a; Taylor and Ellis, 2006). Soil moisture anomalies may affect subsequent rainfall at synoptic (Koster et al. 2000; 2003) or monthly to seasonal (Koster et al. 2004) time scales. Seneviratne et al. (2006) show shifts in regions of strong coupling induced by climate change on multi-decadal time scales. The monthly to seasonal time scale is particularly relevant, as it holds promises for improving seasonal forecasting by exploiting the predictability contained in the soil moisture state (Douville et al. 2009).

The hydroclimate in areas with a strong annual cycle, like monsoon regions or areas affected by tropical convection, displays strong spatial and temporal gradients of the strength of land-atmosphere interaction at the seasonal time scale. Land-atmosphere interaction and, in particular, anomalous soil moisture under conditions of long soil memory, are held partly responsible for anomalies in the strength or duration of wet or dry episodes in for instance the West-African monsoon area (Koster et al. 2004; Douville et al. 2007).
Recently, Dirmeyer et al. (2009) developed an elegant framework in which a series of observable correlations are indicative of a strong land-atmosphere interaction and associated predictability. In order to have a strong and predictable atmospheric response to soil moisture anomalies three conditions should be met. First, surface evaporation is positively correlated with soil moisture. Negative correlations point at conditions where evaporation is depleting the soil reservoir and is primarily limited by available energy or atmospheric demand. Second, evaporation is positively correlated with soil memory. This criterion ensures that anomalous wetness conditions are actually remembered in the subsequent period. Third, atmospheric recycling of water is positively correlated with soil moisture. This ensures that the atmosphere is actually responsive to local wetness anomalies, and that precipitation is not entirely driven by remote advection and/or atmospheric circulation. Their analysis based on a mixture of multiyear (surface) model results and observational datasets reveals that only few areas in West Africa show a strong land-atmosphere coupling in either of the main seasons.

The statistical correlations in the analysis of Dirmeyer et al. (2009) are well interpreted in terms of general behavior of the interacting land-atmosphere system. However, they do not reveal a lot of information on the responsible mechanisms that play a role in this interaction. Dirmeyer et al. (2006) and Guo et al. (2006) address the surface evaporation response to soil moisture and radiation to explain the multi-model spread in the analysis of regions of strong land-atmosphere coupling presented by Koster et al. (2004). A closer look at atmospheric processes is needed to understand and model this complex interaction properly. However, the large number of degrees of freedom in
the atmosphere complicates a comprehensive (preferably observation based) experimental set-up aiming at diagnosing the atmospheric control on land-atmosphere interaction. Findell and Eltahir (2003a,b) introduced a framework in which a single-column model was driven by observed atmospheric profiles, and where the sensitivity of convective triggering to soil moisture conditions was evaluated. They presented maps of systematic positive and negative feedbacks over the US, conditioned on the Convective Triggering Potential (CTP) and a measure of the near-surface dewpoint depression (HIlow). Betts (2004) carried out a range of evaluations of Global Circulation Model (GCM) outputs focusing at the role of LCL, clouds and radiation on the local land-atmosphere interaction. Also Regional Climate Models (RCMs) have been used by a number of authors to assess the sensitivity of the regional hydroclimate to anomalous moisture conditions. Like the work of Findell and Eltahir (2003b) both positive and negative feedbacks are found depending on the governing conditions and processes (Schär et al. 1999; Kanamitsu and Mo, 2003; Cook et al. 2006; Fischer et al. 2007; Bisselink and Dolman, 2008). Most of these studies consider a number of cases, but systematic evaluation of the coupling characteristics at multiyear time scales has hardly been carried out.

In this study we use a variety of diagnostics to identify the regions and seasonal timing of systematic land-atmosphere interaction in Western Africa on a climatological time scale. This area includes regions of strong coupling as indicated by the work of Koster et al. (2004), and is an ideal testbed for exploring a suite of coupling diagnostics due to strong seasonal and spatial gradients of both land surface and atmospheric processes acting on the moisture budget. Following largely the correlation framework
of Dirmeyer et al. (2009) we first identify such regions in a 19-year hind-cast simulation (1989 – 2007) with a Regional Climate Model. Subsequently, we evaluate the sensitivity of a number of atmospheric key properties (LCL, CTP, HIlow) playing a role in land-atmosphere coupling to soil moisture conditions. The model used reproduces the observed seasonality in precipitation very well while maintaining sufficient degrees of freedom in the interior to allow realistic land-atmosphere feedback processes. By doing so, we make use of the capability of regional climate modeling in representing land surface and atmospheric processes and their interaction under conditions that are constrained by observed large scale atmospheric boundary conditions.

In the following we will detail the diagnostics and frameworks. The modeling set-up and the climatological verification are briefly described. After presenting the results on the identified areas and the response of the atmospheric key variables, we will argue that a systematic impact of soil moisture anomalies on local precipitation is strongly constrained by a mixed occurrence of positive and negative feedback processes, and by a strong control of the climatological seasonal cycles of the atmospheric key variables.

**Definition of diagnostics**

For a strong mutual interaction between the surface and the atmosphere both surface evaporation and precipitation must be governed by local moisture conditions. In our set-up we retain two out of the three criteria of Dirmeyer et al. (2009): a collocation of a strong positive anomaly correlation between evaporation and soil moisture, and a strong positive correlation between soil moisture and recycling ratio. The criterion
involving a strong correlation between evaporation and soil memory is believed crucial for the potential contribution of soil moisture information to the hydrological predictability at monthly or longer time scales, but a weak correlation does not preclude the existence of a strong interaction at shorter (daily to monthly) time scales.

Correlation between daily soil moisture and evaporation

For this study soil moisture $W$ is taken as the model value cumulated over the top 1 m of soil (see model description below). It thus reflects the soil water that can be transported to the atmosphere via vegetation transpiration within a seasonal time scale. The correlation between daily soil moisture $W$ and evaporation $E$ is calculated after removal of the mean seasonal cycle, calculated by averaging each calendar day in the 19-yr timeseries. No smoothing or spatial filtering was applied to these fields. Monthly averages of anomalies of $W$ and $E$ are used to calculate the correlation coefficients. The significance of the correlation is determined by a one-sided t-test (significance level 95%), where the number of degrees of freedom is determined by the number of valid values within a given averaging period (maximum about 90 days $\times$ 19 years for seasonal averages) divided by a measure of the soil moisture time scale. This time scale was defined as the time lag at which the soil moisture autocorrelation drops below $1/e$ (the e-folding time scale). For each day in the entire record the autocorrelation was calculated with a backward time lag, and a mean seasonal memory time scale was defined as the average e-folding time scale of all days of each simulation year within that particular season.
Correlation between recycling ratio and soil moisture

The recycling ratio was calculated by a “Lagrangian” method (Dominguez et al. 2006), in which for each 6-hourly model output interval with precipitation the moisture budget of a series of upstream model columns was integrated in order to estimate the source area of the precipitation. By vertically integrating the product of the horizontal wind and atmospheric moisture content at each model level a trajectory along which the moisture column $q$ is advected was constructed, pointing at the next upwind model column $x$. The ratio $E/q$ was integrated over a number of columns until a specified distance $L$ from the originating column was reached. The recycling ratio $R$ can then be shown to be given by (Dominguez et al. 2006; Bisselink and Dolman, 2008):

$$R = 1 - \exp \left( - \frac{1}{\Delta x} \int_0^L \frac{E(x)}{q(x)} \, dx \right) \quad (1)$$

where $\Delta t$ is the processing time step (6 hours) and $\Delta x$ the horizontal distance traveled within a time step. The procedure was applied to all 6-hourly intervals in a given month to calculate a monthly recycling ratio. Values of $L$ were varied over a range between 100 and 1000 km. Although the overall value of $R$ increases with $L$ the spatial and temporal pattern of $R$ is fairly insensitive to the choice of $L$, and values calculated with $L = 500$ km were used. As before, a significant correlation between monthly $R$ and $W$ was determined by a $t$-test with the number of degrees of freedom set by the
number of days in the considered period divided by the soil moisture memory time scale.

Definition of regions with significant coupling

A seasonal mean correlation was calculated considering all monthly anomalies of $W$ and monthly values of $E$ and $R$. The conventional meteorological seasons (DJF, MAM, JJA, SON) were selected for each location, in spite of the fact that at some locations (for instance the northern edge of the West-African monsoon area) the typical annual cycle of succession of dry and wet episodes does not coincide with these time intervals. Areas where both $W$ and $E$, and $W$ and $R$ show a significantly positive correlation are identified as areas prone to strong land-atmosphere interaction at the climatological time scale. In these areas evaporation is higher when soil moisture is higher, showing a control of soil moisture on evaporation rather than vice versa. Also, a higher recycling ratio for wetter soil conditions points at atmospheric conditions where precipitation is at least partly controlled by the local surface conditions, and not entirely due to remote advection of moisture. A spatial smoothing to the significance levels was applied to yield spatially consistent patterns. Grid points are only considered if for six out of the adjacent $3 \times 3$ grid boxes a significant correlation of the same sign is found.

Atmospheric properties

For each grid point and each day the Lifting Condensation Level (LCL) is computed from the daily mean air temperature $T_2$ and dewpoint temperature $T_d$ both at 2m height. The LCL is defined as the intersection of a dry adiabatic lapse rate from $T_2$ and
a moist adiabatic lapse rate from $T_d$. As it is closely related to the surface relative
humidity (Betts, 2004) it generally increases with decreasing soil moisture content.
However, this sensitivity is strongly controlled by atmospheric processes affecting the
thermodynamic structure of the planetary boundary layer and above.

The Convective Triggering Potential (CTP) is a measure for the atmospheric ability to
trigger convection (Findell and Eltahir, 2003a). It is defined as the vertically integrated
early morning (6 UTC) difference between the atmospheric temperature $T$ and the
moist adiabatic lapse rate $T_m$ in the range between 100 and 300 hPa above the
surface. This range is considered to be critical as surface processes may modulate the
LCL and the atmospheric boundary layer (ABL) within this range. During most
conditions the ABL will reach 100 hPa above surface, but 300 hPa above surface is
rarely exceeded. The moist adiabat is calculated by assuming a saturated parcel ascent
from 100 hPa above the surface and accounting for the heat release (and temperature
increase) as condensation occurs. The energy released when condensation occurs may
be an additional source of buoyancy, possibly triggering free convection depending on
the CTP. Negative values of CTP ($T$ on average exceeds $T_m$) indicate a stably stratified
atmosphere in which no convection can occur. Very high CTP-values are indicative of
likely occurrence of (wet or dry) free convection.

A second variable in the framework of Findell and Eltahir (2003a) distinguishes
between wet and dry atmospheric conditions, in relation to the formation of
precipitation from convective events. They define a humidity index HI$_{low}$ as the sum of
the dewpoint depression ($T - T_d$) at 50 and 150 hPa above the surface. Very high
values of $H_{\text{low}}$ are indicative of dry conditions in which no precipitation will occur as the air is too far away from saturation. Very low values will very likely produce precipitation, regardless the state of the surface or convective activity.

In their CTP – $H_{\text{low}}$ framework Findell and Eltahir (2003a) define a set of conditions in which the soil moisture state is likely to influence the occurrence of convective precipitation. In many cases (CTP < 0, $H_{\text{low}}$ too low or too high) precipitation is independent of the surface energy partitioning. For relatively low values of $H_{\text{low}}$ and positive CTP precipitation is favored over wet soils as the surface provides a source of moist static energy that can convert into convective precipitation. Wettening an already wet soil implies a positive feedback loop. Note that this positive feedback has a different nature than the positive feedback implied by e.g. d’Andrea et al. (2006) and Bierkens and van den Hurk (2008), which is based on atmospheric moisture budget considerations rather than on the thermodynamic properties of the atmosphere.

Under dryer conditions and higher CTP values, convection is favored over dry soils which force the LCL to reach to higher levels, a negative feedback.

Set-up and brief verification of the RCM

The RCM considered here is an upgrade of the Regional Atmospheric Climate MOdel (RACMO) version 2.1 (Van Meijgaard et al. 2008). It uses a semi-Lagrangian dynamical formulation and the physical parameterization of the European Centre for Medium-range Weather Forecasting (ECMWF), so-called Cycle 31 (ECMWF, 2007). It carries the soil parameterization presented by Van den Hurk et al. (2000) and the parameterized convection is described by Bechtold et al. (2004).
RACMO2.1 is used extensively for regional climate downscaling (e.g. Lenderink et al. 2007) and evaluation of various components of the physical parameterization (e.g. Zadelhof et al. 2007). The simulation used in the present study is a regional downscaling experiment focusing on the West-African monsoon area applied in the context of the European Commission sponsored project ENSEMBLES (Hewitt and Griggs, 2004). The domain covers the area (38.72°W, 23.32°S, 34.76°E, 38.72°N) at 0.44° resolution (approximately 50 km) and 40 vertical levels. In all analyses and plots a boundary relaxation zone of 10 grid points on either side was excluded. The hindcast simulation was carried out using ECMWF Interim Reanalysis data (Uppala et al. 2008) as lateral boundary conditions for the period January 1989 – November 2007. A 3 year spin-up using ECMWF 40-yr Reanalysis data (Uppala et al. 2005) was applied covering 1986 – 1988. From an evaluation with observed precipitation fields, an apparent wet bias during the spin-up period was reduced considerably upon the introduction of ERA-Interim lateral boundary conditions from 1989 onwards.

The soil moisture $W$ used here is defined as the total water column in the top 1 m of the soil grid, which contains 4 levels up to a depth of 2.89 m. Although stratiform and convective precipitation was stored separately, only total precipitation is considered in the analysis.

Although a full verification of the RCM is not the scope of this study, a decent representation of the main hydrological cycle needs to be confirmed. Figure 1 shows a mean seasonal spatial distribution of precipitation, compared with the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data (Xie and Arkin...
1997). Evidently both the location and order of magnitude of the seasonal mean precipitation are well reproduced by the RCM. However, anomaly correlation coefficients between monthly RCM and CMAP data vary across the land area between 0.2 and 0.6, which implies a poor reconstruction of the year-to-year variability of monthly mean precipitation (not shown). Anomaly correlations between precipitation from the RCM and the driving ERA-Interim data are higher near the boundaries of the model domain, but drop to similarly low values in the West-African monsoon area. Apparently the model has considerable degrees of freedom to adjust its interior hydroclimate away from the forcing boundaries. Therefore, indicators for variability and land-atmosphere interaction, under investigation here, are considered to be affected by modeled atmospheric and land processes, and hardly constrained by the lateral forcing.

**Regions of strong land-atmosphere interaction**

A strong systematic hydrological feedback between land and atmosphere requires the simultaneous sensitivity of evaporation to soil moisture and of precipitation to atmospheric water content (Dirmeyer 2006). In our setup areas where these sensitivities occur are indicated by significant correlations between $E$ and $W$ and between $W$ and $R$.

Figure 2 shows the areas with significant correlation between $E$ and $W$ anomalies. In the core of the heavy precipitation area around the equator the correlations tend to be negative, indicating evaporation to be controlling soil moisture content (by depletion of the reservoir) rather than vice versa. In the dry Sahara and Kalahari deserts the
correlation is weak owing to the small variability of either signal. But in a major portion of the domain significant positive correlations are found. This is in broad agreement with Dirmeyer et al. (2009), who base their findings on offline simulations with an ensemble of land surface models driven by observed precipitation and radiative forcings.

Figure 3 shows the similar plot, but for the correlation between soil moisture $W$ and recycling ratio $R$ using $L = 500$ km. Results are very similar for recycling ratio’s calculated with other values of $L$. $R$ is only defined when precipitation is present, which precludes any coherent signal in the deserts.

The strongest and most coherent positive correlation patterns are shown in JJA in the West African monsoon area, and in the seasons following the main wet period, MAM and SON on the Southern hemisphere, and SON in the a region south of the Sahel. The JJA monsoon signal is probably reflecting interannual variability in the spatial extent of the West African monsoon. Apparently, surface moisture conditions are rather variable and co-varying with the recycling ratio. High recycling ratios during wet conditions imply conditions where precipitation is partly determined by local evaporation; increases in water supply from the surface increase precipitation. Negative correlations indicate wet soil anomalies by rainfall originating from remote areas. This particularly applies to the equatorial tropics in all seasons, and a narrow strip in the Sahel during SON. Again, results are similar to the findings of Dirmeyer et al. (2009), including the alternating negative-positive-negative signal between $10^\circ N$ and the equator in SON.
In Figure 4 the areas where the correlations shown in Figures 2 and 3 are significantly positive are indicated per season. Also shown is the seasonal mean soil moisture memory time scale (the e-folding time scale of lagged correlations). The simultaneous presence of the two positive correlations is indicative for a systematic influence of soil moisture anomalies on precipitation at seasonal time scales during the 19 year analysis period. This influence is strongly constrained, and basically limited to the northern edge of the West-African monsoon in JJA and some scattered areas during the subsequent drying stage in SON, and the equatorward edge of the monsoon in the onset periods (MAM on Northern hemisphere, SON on Southern hemisphere). The South-Africa area is within the influence radius of the lateral relaxation of the RCM to ERA-Interim fields, which possibly introduces model tendencies that are difficult to interpret in terms of atmospheric responses to land surface conditions.

In the study of Koster et al. (2004), which was confined to a single JJA season, roughly the same Sahelian area is highlighted as in Figure 4. They use a coupling strength diagnostic measuring the degree to which precipitation variability is affected by soil moisture anomalies. In Figure 4 a different metric is plotted, but aiming at a similar connection between the surface wetness and precipitation.

Further analyses of the land-atmosphere interaction using RCM model output concentrate on two contrasting but sensitive areas (see boxes in Figure 4): the Northern Sahel located between 12°W – 8°E and 12°N – 17°N, and the inland Tropical area covering Chad, Central African Republic and southern Sudan between
The former region shows positive correlations in JJA and somewhat in the subsequent drying season, whereas the latter region has low correlations in all seasons but MAM. Figure 5 shows the monthly mean values of evaporation and recycling ratio as function of $W$ averaged for these two areas. Monthly mean values are labeled and colored by the season. For evaporation the seasonal cycle of the Sahelian area shows a larger amplitude and is shifted in time compared to the Tropical domain. Evaporation gradually increases with $W$ but a much stronger sensitivity is shown in the drying cycle in the Sahel, where high radiative inputs and availability of soil water cause a rapid depletion of the soil reservoir. In the tropical subdomain this rapid decline of evaporation does not take place until the boreal winter season (DJF), and little difference in sensitivity $\Delta E/\Delta W$ between JJA and SON is observed.

For recycling ratio the situation is different. In the Sahelian area the overall recycling ratio is highest in JJA, and also the sensitivity $\Delta R/\Delta W$ is only clearly positive during the JJA season, allowing a systematic land – atmosphere feedback. In the tropical area a strong dependence of $R$ on $W$ is apparent in SON, when a rapid decline of $R$ from September to November takes place. In spite of this strong dependence a lack of soil moisture control on evaporation prohibits a strong land – atmosphere feedback in this area during JJA and SON.

The MAM signature in the tropical and Sahelian subdomains shown in Figure 4 can also be understood from a different phasing of the seasonal cycle of $\Delta E/\Delta W$ in these two areas: although $E$ strongly increases with soil water in the Sahelian spring season,
the limited water availability does not allow a sustained evaporation or recycling. In the tropical area the wet season has clearly started by the end of MAM, and recycling ratios are positively affected by additional moisture availability.

Key surface-atmosphere relationships in interaction regions

The response of the precipitation features to soil moisture anomalies is governed by both land surface and atmospheric processes. While several studies have explored the sensitivity of precipitation to changing land surface conditions (see references in introduction), only few systematically address the atmospheric conditions that must be met in order to allow a strong land-atmosphere feedback.

Lifting Condensation Level and Convective Triggering Potential

Among others, Betts (2004) use the relation between Lifting Condensation Level and soil moisture to diagnose regions of strong interaction while exploring results from NCEP and ECMWF reanalysis products. A strong sensitivity of the LCL to soil moisture anomalies is at the origin of a number of subsequent feedbacks: boundary layer mixing up to the level of free convection, cloud formation and shortwave and longwave radiative responses when condensation occurs, or eventually triggering or fuelling of convection.

Figure 6 (top row) shows an aggregated picture of the relation between LCL and soil moisture in both subdomains. A general tendency of lower LCL with higher soil moisture is evident, but both areas expose a similar asymmetric seasonal cycle, with a low LCL and low sensitivity to soil moisture in the major wet season, and a steeply
increased LCL and sensitivity in the subsequent drying phase. Thus, in this drying phase a given soil moisture anomaly has a significantly stronger impact on the LCL than a similar anomaly during the period of wetting. Differences in the atmospheric configuration between these two phases are apparently not only reflected in the seasonal cycle of precipitation, but also in the sensitivity to the surface conditions.

A higher LCL is also positively correlated to a higher Convective Triggering Potential (CTP) (Figure 6, middle row). Both CTP and LCL values are rather low and not very variable during the core wet season (JJA) in both regions. Larger systematic excursions are shown in both the wetting and the drying seasons. The relationship between CTP and LCL is fairly similar in both seasons in the Tropical subdomain, but in the Sahelian area lower LCL values are associated with enhanced CTP in the SON season, presumably giving rise to easier convective triggering due to LCL rise.

The bottom row in Figure 6, showing the relation between the low level dewpoint depression HI\_low and soil moisture, reveals an important constraint on strong land-atmosphere interaction during the entire seasonal cycle. For the Sahelian area HI\_low in JJA is on average confined to values < 15 K (consistent with the range found by Findell and Eltahir, 2003a; see below) but quickly reaches very high values in the subsequent dry season, particularly from October onwards. Although relatively small soil moisture perturbations could reduce HI\_low considerably in this steep regime, the atmosphere is often too dry to form precipitation, which implies a strong constraint on the control exerted by soil moisture on the precipitation formation. In the Tropical domain HI\_low stays well within the “precipitable range” < 15 K in all seasons but DJF, but the
variability in soil moisture conditions in particularly SON is very small due to the persistent precipitation, which also reduces the impact of soil moisture anomalies on regional precipitation to a minimum.

CTP, Hi_low and soil moisture anomalies

In the CTP – Hi_low framework of Findell and Eltahir (2003a,b), too low or too high values of Hi_low rule out any surface influence on convective triggering, as the atmospheric structure is overruling any surface anomaly. In a small range of Hi_low – CTP values surface conditions do matter: low Hi_low (between about 5 and 10K) and positive CTP favor convection over wet surface conditions implying a positive feedback mechanism. Higher Hi_low values (between 10 and 15K) and CTP-values well above zero are preferred for convection over dry soils. They use a modeling approach in which for a given day surface wetness conditions are varied and the convective response is explored. Such an experiment could be repeated with an RCM (by running a small ensemble with variable soil moisture conditions around a reference run, for instance applied by Fischer et al, 2007), but this experiment was not carried out for the present study.

Instead, the potential role of the soil wetness condition on the atmospheric ability to form precipitation has been investigated by directly relating soil moisture to the CTP – Hi_low regimes. Assuming the CTP and Hi_low thresholds proposed by Findell and Eltahir (2003a) to be generally applicable, we can separate the occasions where convection is favored over wet soils from conditions with dry soil advantage or no soil control. Figure 7 shows the probability of wet soil advantage conditions (p_{WSA}), defined as the...
relative number of days in every season where \( CTP > 0 \) J/kg and \( 5 < H_{low} < 10 \) K.

Figure 8 shows the analogous probability \( p_{DSA} \) for atmospheric conditions with a dry soil advantage (\( CTP > 150 \) J/kg and \( 10 < H_{low} < 15 \) K). Only points are shown where >5% of the days in the indicated seasons are within the indicated regime. Although the general applicability of the chosen thresholds may be disputed, the spatial signature of the results is not very sensitive to the choice of the threshold values. Reducing for instance the critical value of \( H_{low} \) where a transition from a wet to a dry soil advantage regime occurs from 10 K to 8 K obviously decreases \( p_{WSA} \) and increases \( p_{DSA} \), but these changes occur in the same domains as shown in Figures 7 and 8. In most of the domain the atmospheric conditions were either in the wet soil or dry soil advantage regime for more than 85% of the days when rain occurred (not shown).

In general, wet soil advantage conditions are more frequent than dry soil conditions. The areas where a mixture of wet and dry favoring conditions occurs do coincide near the outermost limits of the wet seasons, and dry soil advantage is barely seen in the deep convective core of the rain seasons. Thus, according to this diagnostic positive feedback occasions (where convection is triggered over wet soils) are more frequent than negative feedback. In particular positive feedbacks remain possible in the Northern edge of the Sahelian rainfall region in SON, when the major rainfall systems are on their retreat southwards. However, outside the tropical rainfall zone positive and negative feedback occurrences are collocated in the same areas and seasons. This implies that conditions with wet or dry soil advantage do alternate, and a systematic positive or negative effect of soil moisture anomalies on convective triggering is
difficult to be established. This introduces an extra constraint for a strong systematic role in soil moisture on precipitation events.

The results show that for $CTP > 0$ relatively low near surface dewpoint depressions ($< 10$ K) occur more often than higher values of $HI_{low}$. To assess whether this is related to the soil moisture conditions in the RCM runs, an additional check is performed. For each day where rain occurred the atmospheric condition was labeled as either wet soil or dry soil advantage. The soil moisture content of the previous day was averaged for each of these two regimes, and labeled as $W_{WSA}$ and $W_{DSA}$ for the soil moisture content in the rainy wet soil and dry soil advantage regimes, respectively. A zero-hypothesis was tested with a Student's t-test that $W_{WSA}$ is similar to $W_{DSA}$. The shaded areas shown in Figure 9 indicate regions where there is a 95% probability that this is not the case, i.e. $W_{WSA} \neq W_{DSA}$. This is a less stringent test than to demand that $W_{WSA} > \bar{W}$ (the climatological mean soil moisture content) and $W_{DSA} < \bar{W}$. To further reduce the scatter in the data the same smoothing was applied as before: only locations where at least 6 out of 9 adjacent grid boxes showed a significant difference of the same sign are plotted.

Positive numbers support the assumption that in an atmosphere with wet soil advantage conditions ($HI_{low} < 10$ K and $CTP > 0$ J/kg) precipitation is formed easier when the previous-day soil moisture is higher than the soil moisture content values that are associated with precipitation events occurring at dry soil advantage conditions ($HI_{low} > 10$ K and $CTP > 150$ J/kg). Precipitation is then considered to be related to the effect of the soil moisture content on the moistening of the lower atmosphere (wet soil
advantage conditions) or lifting the LCL to a sufficient height to promote convection (dry soil advantage conditions). The signal shown in Figure 9 does not appear very coherent. At the edges of the wet seasons statistically different soil moisture contents for wet soil and dry soil advantage regimes are shown, and positive ($W_{WSA} > W_{DSA}$) values are clearly dominant. In the boxes with significant positive correlations between $E$ and $W$ and between $W$ and $R$ (Figure 4) the signal in Figure 9 is not covering all grid points. Also, areas with significant differences between $W_{WSA}$ and $W_{DSA}$ are found at other locations in other seasons, where Figure 4 does not point at a strong atmospheric response to soil moisture anomalies.

Discussion and conclusions

We have used correlations between soil moisture, evaporation and recycling ratio generated with a Regional Climate Model nested in meteorological reanalysis data during a 19-year period to identify regions of potential control of surface wetness conditions on rainfall in a large African domain. The correlation framework was used before by Dirmeyer et al. (2009) using observations and offline model results covering the entire globe. For the region of interest we find similar spatial and seasonal patterns of areas where evaporation and recycling ratio are partly controlled by soil moisture: the northern edge of the West-African monsoon in JJA, and a number of smaller regions including a tropical Northern hemispheric region in MAM. In these regions and seasons, evaporation is substantial and to some extent governed by the available soil moisture content, and not only by available radiation and/or atmospheric demand for water. During the dry seasons in the Sahel evaporation rates and soil moisture are too low to detect a substantial correlation above the noise level, and in the heart of the
wet season soil moisture is abundant and not constraining evaporation. A strong
correlation between soil moisture and recycling ratio points at the local origin of
moisture for precipitation. In the tropical zones around the equator moisture advected
from the oceans is presumably the primary source of moisture. Away from the equator
significant correlations between soil moisture and recycling ratio exist during the
transition seasons SON and MAM.

In the regions of potential land-atmosphere interaction, we analyzed the seasonal
cycles and soil related variability of a number of key atmospheric variables. The Lifting
Condensation Level (LCL) displays a pronounced seasonal cycle in harmony with the
migration of the precipitation systems. Low values are associated with the wet season
as the soil becomes wetter, while during the drying stage LCL rapidly rises with
decreasing soil moisture. This rapid increase points at a strong sensitivity of the
atmospheric condition to soil moisture conditions. This seasonal cycle is typical for
every location within reach of the seasonal precipitation (either ITCZ or monsoon),
although the timing over the year varies with location. However, also for areas without
significant correlations between soil moisture, evaporation and recycling ratio this
asymmetry in atmospheric sensitivity to soil moisture conditions is found apparent.

Thus other mechanisms must be in place as well to explain a strong atmospheric
sensitivity to surface wetness conditions.

When rising air comes to condensation extra energy is released that may trigger moist
convection. From a comparison between the two key regions the relationship between
LCL and Convective Triggering Potential (CTP) shows a slightly different seasonal
signature. In the region with strong coupling in JJA (Northern Sahel) a hysteresis between LCL and CTP appears: during the drying phase the LCL is lower at a given CTP-value than during the wetting season MAM. This may favor the release of more convective potential energy, providing a link between the soil state and the convection. However, the generally dry state of the atmosphere outside the main wet season forms an extra constraint on the potential role of soil moisture in convective triggering. In the tropical area the LCL – CTP relation is more symmetric, and the LCL rise in the drying season does not affect CTP differently.

From an evaluation of previous-day soil moisture under conditions of rainfall it was seen that there are many locations where soil moisture is indeed higher for wet soil advantage conditions than for dry soil advantage. However, this feature is not very coherent. Wet soil advantage conditions – associated with a positive feedback as precipitation is promoted under wet soil conditions – are more widespread and frequent than dry soil advantage conditions, and remain present in the Northern Sahel during the retreat of the rainfall in SON.

The diagnostics analyzed here do indicate a positive contribution of soil moisture anomalies to the occurrence of rainfall on a climatological time scale, but in general the areas where this coupling is strong are fairly small. Precipitation in the tropical convergence zone and the adjacent trade wind regimes is dominated by migrating and growing mesoscale precipitation systems, whose dynamics are dominated by large scale atmospheric features. Local moisture anomalies may influence the activity or trajectory of these rainfall mechanisms (Taylor et al, 2007), but the spatial scale at
which this interaction is active is probably too small to be picked up by the RCM and the diagnostics used in this study.

Land – atmosphere interaction is governed by a combination of surface and atmospheric processes. Although the model used is only an approximation of the true processes in nature and possibly shows biases with respect to the behavior of land surface and convection parameterizations (e.g. Hohenegger et al, 2009), the results do show that for the limited number of areas where land-atmosphere coupling is found to be significant the relevant processes needed for an atmosphere to respond to (anomalous) soil conditions are in place. From a statistical point of view the role of surface conditions in the precipitation dynamics is generally not overwhelming, even under conditions where soil moisture exerts a significant influence on surface evaporation. The seasonal cycle of the atmospheric properties is an important modulator of the degree to which hydrological surface anomalies extend affect the precipitation formation process. A strong sensitivity of evaporation to soil moisture does not lead to a response of rainfall when the atmosphere is too dry to form precipitation. However, the study focuses on systematic land – atmosphere interaction with a climatological perspective. The small values of the general statistical correlations found in the 19-year time record do not preclude the existence of short anomalous episodes when soil moisture conditions do have a strong effect on local precipitation. A similar contradiction can be formulated for Central European summer conditions: in the systematic analyses of Koster et al. (2004) and Dirmeyer et al. (2009) the mean impact of soil moisture anomalies on summertime precipitation are small, but extreme events like the 2003 heatwave have triggered many studies that
highlighted the importance of the land–atmosphere feedback in maintaining the anomalous conditions (e.g. Ferranti and Viterbo 2006).

The study was designed to demonstrate a number of diagnostics that in principle could be observed, and do not require model sensitivity runs like the set-up of Findell and Eltahir (2003a), Koster et al. (2004) and Hohenegger et al. (2009). However, further work is needed to verify the RCM results with true observations. Also the diagnostic framework could still be developed further. We already referred to the importance of quantifying conditional predictability in cases where systematic land–atmosphere interaction is small but where during individual episodes a strong soil control on the regional hydrological cycle may exist. Also, diagnostics that – other than this study – measure the potential influence of anomalous soil moisture conditions on precipitation in remote areas (see e.g. the case studies by Beljaars et al. 1996; Haarsma et al. 2009) remains a relevant topic for research.

**Acknowledgements**

The RCM runs are carried out under the auspices of the ENSEMBLES project (see http://www.ensembles-eu.org). Geert Lenderink has presented results from this study to other groups participating in ENSEMBLES. A land-atmosphere coupling workshop co-sponsored by the GEWEX panel GLASS (www.gewex.org/glass.html) and the EU-project WATCH (http://www.eu-watch.org) in De Bilt in June 2008 gave a lot of inspiration for this study. CMAP Precipitation data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at http://www.cdc.noaa.gov.
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Figure captions

Figure 1: RCM Modeled (top row) and CMAP observed (bottom row) seasonal mean precipitation for 1989 – 2007 (mm/day). Only land points are shown. RCM data have a spatial resolution of $0.44^\circ \times 0.44^\circ$, and CMAP data are at $2.5^\circ \times 2.5^\circ$.

Figure 2: Areas with significant correlations between monthly evaporation and soil moisture anomalies. Plotted are areas with a 95% significant correlation between all monthly values in 1989 – 2007 in DJF (upper left), MAM (upper right), JJA (lower left) and SON (lower right). A spatial smoothing was applied that only masks locations where $<2/3$ of all neighboring grid boxes show significant correlations of the same sign.

Figure 3: As Figure 2, but for correlations between soil moisture content $W$ and recycling ratio $R$ ($L = 500 \text{ km}$).

Figure 4: Soil memory (days) in regions with significantly positive correlations between $E$ and $W$ (fig 2) and between $R$ and $W$ (fig 3), for each season. The indicated boxes denote the domains used for further analyses.

Figure 5: Monthly mean values of (top) evaporation versus $W$ and (bottom) recycling ratio versus $W$ averaged for (left) the Sahel domain and (right) the Tropical domain (see boxes in Figure 4). Every number indicates a month in the year. Colors refer to the main seasons (purple = DJF, red = MAM, blue = JJA, green = SON).
Figure 6: Top row: as Figure 5, for the height of the Lifting Condensation Level above the surface. Middle row: monthly mean LCL plotted against Convective Triggering Potential. Bottom row: HI\textsubscript{low} versus soil moisture content. Note that DJF and March HI\textsubscript{low} values are outside the plot scale in the Sahelian region.

Figure 7: Frequency of occasions where wet soil conditions are favorable to trigger convection, diagnosed from 5 < HI\textsubscript{low} < 10 K and CTP > 0 J/kg. Shown are relative number of days per season, p\textsubscript{WSA}. Note the non-linear color scale.

Figure 8: As figure 7 for dry soil conditions favoring convective triggering (p\textsubscript{DSA}, 10 < HI\textsubscript{low} < 15 K, CTP > 150 J/kg)

Figure 9: Significant difference between previous day soil moisture content for cases where CTP and HI\textsubscript{low} indicate wet soils to favor convective triggering and cases with a dry soil advantage (W\textsubscript{WSA} – W\textsubscript{DSA}). A two-sided t-test (95%), and a spatial filter (≥ 6 out of 9 adjacent grid boxes required to have the same significant sign) are used to mask insignificant differences. The boxes shown in Figure 4 are added for geographical reference.
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