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New perspectives on land–atmosphere feedbacks from the African Monsoon Multidisciplinary Analysis

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Abstract

Research into land–atmosphere coupling within the African Monsoon Multidisciplinary Analysis has highlighted the atmospheric impact of soil moisture on space scales of 5 km upwards and time scales of several days. Observational and modelling studies have shown how antecedent rainfall patterns affect new storms in the Sahel. The land feedback operates through various mechanisms, including a direct link to afternoon storm initiation from surface-induced mesoscale circulations, and indirectly via a large-scale moisture transport in the nocturnal monsoon. The results suggest potential for significant improvements in weather forecasting through assimilation of satellite data. Intriguing questions remain about the importance of vegetation memory on seasonal–interannual scales. Copyright © 2011 Royal Meteorological Society

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1. Introduction

The West African Monsoon is considered to exhibit strong sensitivities to the land surface at a range of time and space scales. Studies using climate models by Charney (1975), Zeng *et al.* (1999) and Xue and Shukla (1993) amongst others have found feedbacks between vegetation cover and precipitation that may have contributed to the extreme Sahelian drought conditions in the 1970s and 1980s. On the annual time scale, there is some theoretical and observational evidence that pre-monsoon land surface conditions can affect rainfall in the wet season (Eltahir and Gong, 1996; Fontaine *et al.*, 1999) via horizontal gradients in moist static energy. Observational and modelling studies have also shown how soil moisture can affect daily (Clark *et al.*, 2004; Taylor and Lebel, 1998) and weekly (Koster *et al.*, 2006) rainfall. The interest in West Africa as a globally important land–atmosphere ‘hotspot’ meant that land–atmosphere feedbacks provided an integrating focus within the African Monsoon Multidisciplinary Analysis (AMMA).

Prior to AMMA, there were a number of key unknowns relating to land–atmosphere interaction. Whilst there had been several observational campaigns in the region to measure the components of the surface energy balance (most notably HAPEX-Sahel), there was a lack of long-term data to evaluate land surface models across the monsoon region, ranging from the moist tropics in the south to the desert in the north, and incorporating a range of land uses. A study by Philippon and Fontaine (2002) had speculated that a memory of rainfall in the previous year in the Soudanian zone might affect the following Sahelian wet season, yet there was little observational insight into the length of such land ‘memory’. Whilst observational studies had shown a marked response of the planetary boundary layer (PBL) to mesoscale soil moisture patterns (Taylor *et al.*, 2003), it was unclear whether the surface-sensible heat flux gradients could drive significant daytime circulations, as predicted by models. If strong meso- and synoptic-scale circulations were induced by soil moisture, were they of any great relevance for understanding rainfall variability? For example were new storms initiated in mesoscale convergence zones,

or at the larger scale, via changes in the strong nocturnal monsoon flow?

The strategy to answer these questions within the AMMA program involved taking new ground and atmospheric observations and combining them with remotely sensed data and numerical models. Key new results are summarised in this article, which concludes with a discussion of how the science should progress from here.

2. Observations of surface and PBL response to rainfall

The surface energy balance was monitored at sites which spanned a large range of climatic and land cover conditions found in West Africa, and the results are summarised by Seguis *et al.* (2011). Considering feedbacks on the atmosphere, Guichard *et al.* (2009) showed from observations in northern Mali how the seasonal evolution of the radiation balance couples with the surface thermodynamics in the Sahel. Of particular note is the marked increase in net radiation driven by the wet season transition from hot, sandy dunes to cooler, darker vegetated grasslands. Increased net radiation implies enhanced surface moist static energy, consistent with a positive soil moisture-rainfall feedback on the seasonal time scale. The response of the PBL to rainfall on shorter time scales was documented using a unique dataset collected from a wetter region in southern Burkina Faso (Kohler *et al.*, 2010; Schwendike *et al.*, 2010). These studies found strong responses in albedo, surface temperature and Bowen ratio for 2–3 days after a rain event, though once the seasonal vegetation cover was well established, the amplitude of the response weakened markedly. The PBL after the monsoon onset was typically half the value of its pre-onset height due to the weakening sensible heat flux. Throughout the campaign, the diurnal development of convective instability was dominated by changes in the PBL, and recovered within 2 days of the passage of a mesoscale convective system (MCS).

3. Impact of surface variability on the PBL and moist convection

To examine the impact of the above processes on the PBL at the mesoscale, an aircraft campaign was designed to target regions with strong spatial variations in surface fluxes, either from soil moisture or vegetation patterns. The example in Figure 1 (Taylor *et al.*, 2007) illustrates the variability of near-surface soil moisture on scales up to 1000 km associated with the passage of MCS. Land surface models forced by observational estimates of precipitation in the AMMA Land Model Intercomparison Project (ALMIP, Boone *et al.*, 2009) captured these large-scale upper-soil moisture structures (Figure 1(b)), unlike the ERA-Interim

reanalysis product (Figure 1(c)). Assimilation of high-resolution land surface temperature data into a land model (Figure 1(d); Harris and Taylor, manuscript in preparation) illustrates the substantial variability on spatial scales ~ 10 km for which no reliable precipitation estimate exists.

The variations in soil moisture have a substantial impact on surface fluxes, as depicted by the ensemble of nine land models in ALMIP (Figure 2). Daily fluxes of latent (sensible) heat fluxes within the Mali wet feature are up to 100 W m^{-2} higher (lower) than adjacent dry regions. Along the flight track indicated in Figure 1(d), Taylor *et al.* (2007) showed that the PBL temperature was significantly correlated with the land surface temperature on wavelengths as low as 5 km, and furthermore, found a clear correlation between surface-induced temperature gradients and the low-level winds. This observational result was consistent with theory (Baldi *et al.*, 2008), and answered one of the key questions prior to AMMA. Figure 3 presents the PBL variables along the aircraft track from the observations, accompanied by output from a numerical model using alternative surface initialisations (Bastin *et al.*, manuscript in preparation). The ‘DRY’ simulation was initialised using soil moisture similar to that shown in Figure 1(c) (i.e. without the Malian wet feature north of 15.5°N), whereas the ‘WET’ simulation used data from ALMIP (Figure 1(b)). The runs demonstrate the impact of the soil moisture on the PBL temperature gradients and winds. For example, local minima in wind speed in WET (marked ‘X’) are induced by local reversals in the temperature gradient. However, the more realistic WET simulation cannot capture the finer scale variations evident in the observations, and furthermore, neither simulation can reproduce the observed humidity.

There were also important developments in our understanding of how mesoscale soil moisture patterns influence subsequent storms. Analysis of satellite data from hundreds of storms revealed an increase of 33% in afternoon cloud cover over dry soils compared to nearby wetter areas; a negative feedback (Taylor and Ellis, 2006). Such a result can only be explained in terms of variability in surface fluxes as both wet and dry soils were subjected to the same large-scale conditions. An observational case study from an aircraft flight close to a rapidly developing MCS shed new light on this result (Taylor *et al.*, 2010). The first cells developed along a sharp soil moisture gradient before expanding over the dry area. This suggested an important role for the surface-induced circulations discussed earlier in providing a favourable environment for convective initiation, alongside other mechanisms such as orographic forcing and cold pools. Further evidence showing the impact of surface-induced circulations on storm development came from numerical simulations (Gaertner *et al.*, 2010; Gantner and Kalthoff, 2010), observations from forest–crop transitions (Garcia-Carreras *et al.*, 2010) and satellite cloud data around the Mali wetlands (Taylor, 2010).

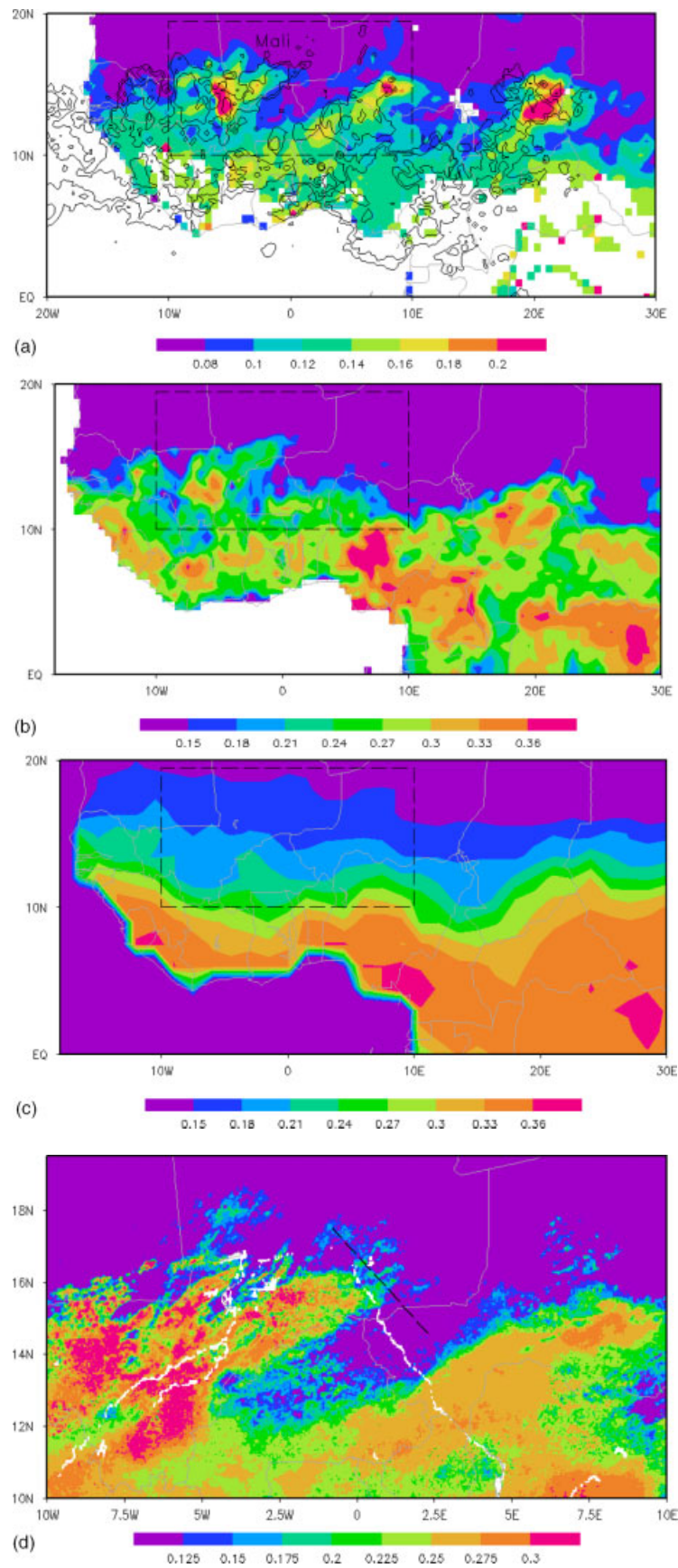


Figure 1. Upper-soil moisture ($\text{m}^3 \text{m}^{-3}$) on 1 August 2006 from (a) the AMSR-E satellite (0–1 cm), (b) an offline simulation of a land surface model forced by ALMIP data (0–10 cm), (c) ERA-Interim reanalysis (0–5 cm) and (d) the offline model in (b) assimilating land surface temperature data at 3-km resolution. Total rainfall for the period 31 July to 1 August is shown by 10 and 30 mm isohyets in (a). The sub-domain of the high-resolution simulation is marked in (a), (b) and (c), and the aircraft track denoted by a dashed line in (d).

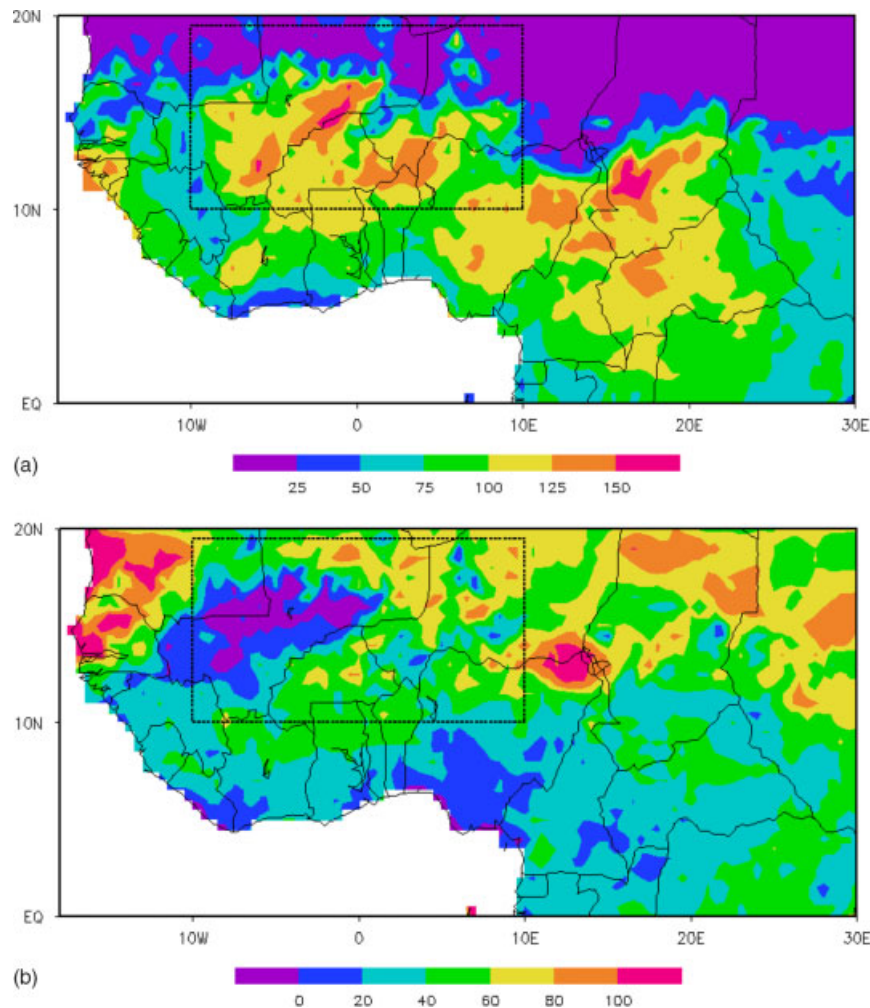


Figure 2. Latent (a) and sensible (b) heat fluxes (W m^{-2}) on 1 August 2006 averaged over nine models using ALMIP forcing.

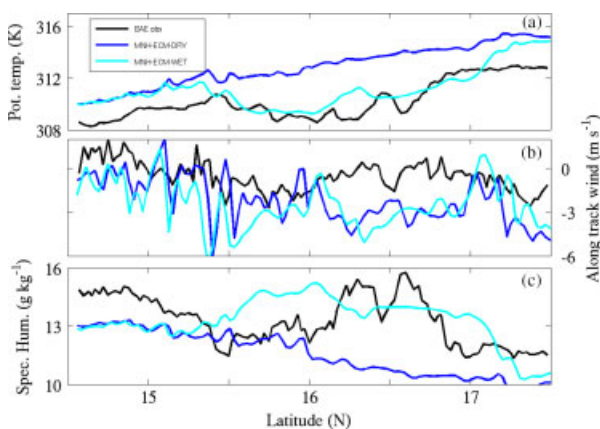


Figure 3. Aircraft observations (black) of PBL potential temperature (K; top), wind component (m s^{-1} ; middle), and specific humidity (g kg^{-1} ; bottom) along the track shown in Figure 1(d) on 1 August 2006. The dark and light blue lines show these variables in numerical simulations initialised using soil moisture from European Centre for Medium Range Weather Forecasting (ECMWF) (dark blue) and ALMIP (light blue) simulations.

Once storms are initiated, our research suggests that various processes may govern the strength, and even the sign, of feedbacks between soil moisture

and individual MCS. There is evidence that mature MCS with well-developed gust fronts can intensify over wet soils due to increased Convective Available Potential Energy (Gantner and Kalthoff, 2010; Taylor *et al.*, 2010). However, this positive feedback may reverse depending on the phase of the diurnal cycle, the convective inhibition and synoptic state, and the scale and orientation of the wet patch relative to the large-scale flow (Gaertner *et al.*, 2010).

The storm-scale feedbacks discussed here are of course embedded within synoptic disturbances. Within AMMA, Parker (2008) built on earlier work (Taylor *et al.*, 2005) to develop a simple dynamical model of coupling between African Easterly Waves (AEWs) and soil moisture. He illustrated how soil moisture evolution can be a dynamically active part of propagating synoptic disturbances. During the AMMA aircraft campaign, one AEW event in particular – the short-lived case of 26–28 July 2006 – exhibited a notable soil moisture anomaly on the synoptic scale (Bain, 2008). Numerical modelling revealed some significant influences of the surface on the AEW, including a meridional shift and reduction in the intensity of the African Easterly Jet (AEJ) when

Table I. Key processes of land–atmosphere coupling on different time and space scales.

Scale	Hours – 1 day	Several days	Intraseasonal	Seasonal–interannual
Plot (e.g. single rain gauge)	Diurnal cycle of PBL growth driven by surface heating (Kohler <i>et al.</i> , 2010)	Surface-PBL response to rain event (Kohler <i>et al.</i> , 2010)	Impact of vegetation on surface thermodynamics (Guichard <i>et al.</i> , 2009)	Land memory (Douville <i>et al.</i> , 2007; Philippon <i>et al.</i> , 2007)
Mesoscale (5–1000 km)	Surface-induced PBL gradients and daytime circulations (Taylor <i>et al.</i> , 2007; Baldi <i>et al.</i> , 2008). Impact of soil moisture on storms (Taylor and Ellis, 2006; Gaertner <i>et al.</i> , 2010; Gantner and Kalthoff, 2010; Taylor <i>et al.</i> , 2010)	Positive feedbacks at convective scales within MCS (Clark <i>et al.</i> , 2004; Taylor and Lebel, 1998), negative feedbacks associated with initiating convection (Taylor and Ellis, 2006)	Impact of longer-lived surface features (vegetation, wetlands) on storms (Garcia-Carreras <i>et al.</i> , 2010; Taylor, 2010)	Unknown
Synoptic–continental (>500 km)	Sahelian heat low anomalies intensify overnight (Taylor <i>et al.</i> , 2005). Diurnal cycle of monsoon and Saharan heating (Parker <i>et al.</i> , 2005)	Soil moisture feedback on wave dynamics (Parker, 2008)	Intraseasonal patterns of surface heating linked to rainfall variability (Taylor, 2008; Dominguez <i>et al.</i> , 2010; Flaounas <i>et al.</i> , 2010; Lavender <i>et al.</i> , 2010)	Soil moisture memory (Eltahir and Gong, 1996; Philippon and Fontaine, 2002; Douville <i>et al.</i> , 2007); interannual vegetation feedbacks (Chamey, 1975; Zeng <i>et al.</i> , 1999)

the soil had dried: it appears that over a drier soil, the deeper boundary layer convection retards the AEJ. In turn, it is likely that this change in the AEJ would retard the propagation of individual MCSs.

4. Feedbacks on intraseasonal to interannual time scales

A major topic of interest across AMMA was the intraseasonal variability in rainfall (Janicot *et al.*, 2011). Rainfall fluctuations on periods ~ 15 days in the Sahel induce a coherent, large-scale response of sensible heat flux from the land due to soil moisture (Taylor, 2008) and insolation (Lavender *et al.*, 2010). Within a propagating AEW, or an intraseasonal synoptic wave, the land induces anomalous heat low type circulations in the northern Sahel which favour the westward propagation of the wave's envelope of rainfall, as observed. The sensitivity of this mode of variability to surface albedo (Flaounas *et al.*, 2010) and the land surface parameterisation (Dominguez *et al.*, 2010) was also tested. Whilst many aspects of the regional simulations were rather sensitive to the land, the timing of the active-break cycles was determined by the atmospheric lateral boundary conditions.

Although the surface memory of each individual storm is short (a few days), the root zone soil moisture, and critically, the vegetation state, depends on an integration of the water balance over much longer periods. A key question therefore is to assess how much of that information is carried over from one season to the next. Using Normalised Difference Vegetation Index (NDVI) data, Philippon *et al.* (2007)

found evidence of an interannual land memory in the grasslands of Sahel. They found a significant increase during June in the correlation of NDVI with maximum NDVI recorded the previous year. The observations suggest a beneficial effect of high productivity in the previous year on the first flush of vegetation when the first rains fall some 9 months later. Although the mechanism remains unclear, it appears unlikely to operate directly via a memory of soil moisture in the shallow root zone of the grasses. That point was illustrated in a General Circulation Model (GCM) study (Douville *et al.*, 2007) which depicted a strong soil moisture memory effect on the monsoon at the end of the wet season, but no evidence of similar processes operating on the interannual time scale.

5. Perspectives on feedbacks and predictability

Through the research in AMMA, we have a much clearer understanding of the dominant land–atmosphere feedback processes operating at different time and space scales (Table I). In particular, it is now clear that transient soil moisture patterns induce dynamic and thermodynamic responses in the PBL on length scales of ten to several thousand kilometres. These processes influence both the lifecycle of individual storms at the mesoscale, and the dynamics of the monsoon circulation, and hence the advection of moisture into the region.

Questions remain concerning the influence of the land on mature MCS, where feedbacks could have a notable impact on seasonal rainfall totals. Notwithstanding this, we are close to making practical use of the knowledge gained in AMMA, both in terms

of bench forecasting (e.g. the use of remote sensing of soil moisture to better predict MCS and AEWs), and in longer term numerical forecasting, where the slow evolution of root zone soil moisture and vegetation relative to the atmosphere may provide additional predictability. Even with the knowledge of soil moisture gained from existing satellites, where quantitative estimates of surface state are far from ideal (Kergoat *et al.*, 2011), we can see an important atmospheric response from case studies and statistical studies. The availability of improved estimates of soil moisture from the new Soil Moisture and Ocean Salinity (SMOS) satellite therefore holds much potential. Similarly, Figure 1 illustrates the potential benefits for short-term forecasts by running land models offline, forced by the best available (ALMIP) observations, to initialise soil moisture. Although we have shown that models produce realistic atmospheric responses to surface soil moisture contrasts in specific test cases, the representation of water vapour remains a big issue (Figure 3(c)), and it is unclear if these models are able to reproduce the full complexity of the feedback. An important result in this context is the low impact of improved soil moisture initialisation (from ALMIP) on 48-h rainfall totals predicted by the ECMWF model (Agusti-Panareda *et al.*, 2010). That study implied that other processes (e.g. cloud, aerosol, moisture divergence) are primarily responsible for the dry bias in the ECMWF model.

On longer time scales, we have limited confidence in the ability of our models to represent the evolution of surface properties over the seasons, and respond correctly to rainfall events. Although global climate models suggest a dominant influence of tropical oceans on West African Monsoon (WAM) variability at interannual to multidecadal timescales, they lack sufficiently accurate descriptions of ecosystem and groundwater dynamics (if they represent these processes at all) to evaluate the land contribution. More difficult still is our ability to simulate with large-scale coupled models the surface–atmosphere feedbacks given the inherent problems with the representation of the atmosphere (notably precipitation) and the impact of rainfall and radiation biases on the land surface fluxes and stores. Within AMMA, techniques are being developed using cloud resolving models to evaluate the representation of feedbacks within coarse scale models.

This calls for a more systematic analysis with a number of models of the impact of improved soil moisture descriptions on atmospheric processes. Such a coordinated experiment would better identify the conditions and processes for which models diverge. This will offer guidance for revisiting AMMA observations and completing the database with results from more targeted field campaigns.

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