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Response of surface energy balance to water regime and vegetation development in a Sahelian landscape

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SUMMARY

The West African monsoon interacts strongly with the land surface, yet knowledge of these interactions is severely limited by the lack of observations of surface energy fluxes. Within the framework of the AMMA project, three eddy covariance flux stations were installed to sample the three main surface types near Hombori (Mali) in the central Sahel at 15.3°N, and a fourth station was installed near Bamba in the northern Sahel at 17.1°N to sample semi-desert conditions. Observed land types near Hombori comprised a grassland growing on sandy soil (near the village of Agoufou), a flooded forest in a clay-soil depression (Kelma), and a bare rocky soil (Eguerit). The energy balance closure at the grassland site was satisfactory, but less so at the flooded forest site. Surface water heat storage during the flood and advection probably were responsible for most of the imbalance.

The daily sensible heat flux (H) was fairly constant throughout the year at Bamba and Eguerit, with only a slight increase during the monsoon season corresponding to increased net radiation. By contrast, the seasonal cycle of the grassland site was marked, with H decreasing during the monsoon season from 70 W m^{-2} in May to 20 W m^{-2} in August. The flooded woodland exhibited the strongest contrast between the dry and wet seasons, with daily sensible heat flux close to zero during the flood. During the peak monsoon season, the two vegetated sites had the highest net radiation and the lowest sensible heat flux, as a consequence of the strong evapotranspiration rates caused by both high soil moisture availability and high leaf area index. Lateral fluxes of water were found to be strong drivers of inter-site sensible and latent heat fluxes variability, with water leaving bare rocky soils as surface runoff and ending in the clay depressions (e.g., Kelma), whereas the sandy soils were locally endorheic, with most of the rainfall being rapidly returned to the atmosphere.

An attempt was made to scale the sensible heat flux up to the scale of the AMMA northern super-site (60 km × 60 km), following a simple scaling scheme, which accounted for the contrasting surface types and water regimes. The super-site average sensible heat flux proved to be close to the grassland sensible heat flux, in part because grassland occupies 55% of the area. A strong spatial variability was caused by the difference in water regime and vegetation type, at a scale large enough to potentially influence the atmospheric properties such as the boundary layer.

Introduction

The West African monsoon (WAM) has been shown to depend significantly on surface–atmosphere interaction, at the large scale (Charney et al., 1975; Nicholson et al., 1998; Zeng et al., 1999; Nicholson, 2000) as well as at the meso-scale (Clark et al., 2004; Taylor et al., 2007; Mohr et al., 2003). The land surface is currently thought to act as a strong amplifier of the WAM inter-annual variability, which is at least partially triggered by ocean SST anomalies (Giannini et al., 2003). As a result, the whole water cycle of the monsoon is affected by the land surface energy and mass fluxes. There is a need to understand and quantify the processes, which control the surface fluxes in West-Africa, as well as to evaluate land surface models (de Rosnay et al., 2006). Evaluation can be performed at the local scale, using flux time series where they exist (FLUXNET, Baldocchi et al., 2001), but it becomes increasingly important to assess the surface fluxes at the landscape scale. Both the average value, which corresponds to the grid-cell of large scale models, and the spatial variability of the fluxes are of interest (e.g. LeMone et al., 2007). The land surface is characterized by a significant heterogeneity created by topography, soil type, land use, and

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land cover. In addition, the surface fluxes are modulated by atmospheric forcings, with precipitation being of utmost importance in semi-arid regions. It has been shown that meso-scale heterogeneity greatly influences the atmospheric boundary layer and thermodynamics, meso-scale circulations, and convection triggering and intensity (LeMone et al., 2007 and references therein, Clark et al., 2004). Modelling studies have suggested that surface heterogeneity potentially has an effect on rainfall in the tropics (Avissar et al., 2004).

Unfortunately, the current understanding of the surface/atmosphere interactions is severely limited by a lack of observations, West-Africa being one of the less instrumented regions of the world. The AMMA/Catch (African Monsoon Multidisciplinary Analyses/Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique) network provides datasets, which can be used to scrutinize land surface fluxes with unprecedented focus and accuracy. For instance, the development of a network of flux measurement stations provides the opportunity to explore the time and space variability of these fluxes along a latitudinal transect, as well as the scaling of the fluxes from local to meso-scale. In this article, surface fluxes measured at 15.3°N and 17°N, over the northernmost AMMA/Catch meso-scale site, in the Malian Gourma, are presented. Instruments were deployed in the central and northern parts of the Sahel, for which no flux observations had been collected previously. The closest documented ecosystems are found in the southern Sahel, near Niamey (Niger), where the SEBEX and HAPEX-Sahel experiments took place, mostly during the 'dry-down' phase of the monsoon (Allen et al., 1994; Gash et al., 1997). The resulting data for millet crops, bush fallow and tiger bush proved critical in assessing model performance, (e.g. Taylor et al., 2002; Kahan et al., 2006). There is a need to carry out in-depth examination of land surface processes over different surface types in the central and northern Sahel regions. The seasonal cycle of the sensible heat, latent heat and radiation surface fluxes for the different landscape types is described and the driving variables are identified. Since lateral water redistribution is crucial to the soil moisture regime and vegetation development in this area, the roles of run-off, run-on and locally endorheic systems on the sensible heat flux are investigated.

Site description

A comprehensive description of the northernmost AMMA/Catch site is provided by Mougin et al. (2009). Hiernaux et al. (2009) describe the vegetation, Samain et al. (2008), Guichard et al. (2009), Frappart et al. (2009) and de Rosnay et al. (2009) document the meteorological, radiation and soil moisture networks. The climate is controlled by the monsoon, with south-westerly winds providing moist air from June to September, and north-easterly Harmattan winds bringing hot and dry air during the rest of the year. Rainfall averages 350 mm at Hombori and 150 at Bamba (semi-desert site of Fig. 1) and is brought by convective systems, mostly from early July to mid-September. The so-called Hombori super-site is a 60 km × 60 km area embedded in the larger meso-scale site, which extends from 14.5°N to 17.5°N (Fig. 1). Within the Hombori super-site, 55% of the area is covered by grasslands growing on sandy dunes (Fig. 2, grey), 35% is bare soil (Fig. 2, white), comprising rocks topped with gravels (20%), and loamy shallow soils (15%), and 10% consist of valleys and low-lands referred to as 'bas-fonds' in French, with clay soil (Fig. 2, black). Ponds and seasonally flooded woodlands are found in the lowest part of these depressions (5%). Sandy dunes are locally endorheic (no runoff except over very short distance, of less than 100 m), whereas bare soils generate substantial run-off into the depressions. Tree cover is low or non existent (of the order of 1%) over bare soil. It is low

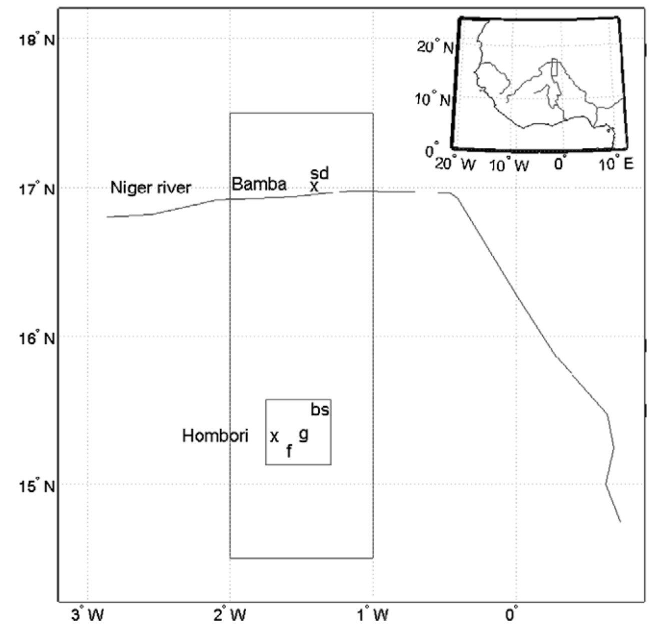

Fig. 1. Map of the meso-scale Gourma site, with the four eddy covariance sites. The semi-desert site (sd) is north of the Niger river, whereas the three others, grassland (g), bare rocky soil (bs) and forest (f), are located in the so-called super-site. (x) are for the villages of Hombori and Bamba.

over grasslands (generally between 0% end 5%), but can reach 60% in flooded Acacia stands in the clay-soil depressions.

Data

Four flux stations were operated in 2005, 2006 and 2007 to sample the three main surface types as well as the latitudinal climate gradient (15.3°N, 17.1°N). Three flux stations were deployed within the super-site of 60 km by 60 km area, as shown in Figs. 1 and 2. As such, they broadly undergo the same climate conditions, apart from rainfall, which can differ, especially when short time scales are considered, such as the scale of an event or a convective cell within an event. In Eguerit, the flux station is installed on a bare, dark, hard pan outcrop. Net radiation has also been measured on nearby bright loamy bare soil during 56 days in 2008. The grassland (Agoufou) grows over bright sandy soil, dominated by annual grasses and forbs with 2% tree cover, mostly scattered *Acacia*, *Combretum*, *Balanites* and *Leptadenia*. Kelma is a seasonally flooded open woodland site, with a 40% tree cover (mostly from *Acacia seyal* and *Acacia nilotica*), growing on a loamy-clay soil. These sites are referred to as "bare rocky soil" (Eguerit), "grassland" (Agoufou) and "flooded forest" (Kelma). In addition to the three super-site stations, a fourth station was installed near Bamba at 17.1°N to sample semi-desert surface at the margins of the Sahara. This site belongs to a different eco-climatic zone (Frappart et al., 2009) and is referred to as the "semi-desert site". The soil is sandy and bright and vegetation is sparse at most, with a few scattered trees, perennial and short annual grasses. At the three super-site stations, grass leaf area index (LAI) and tree plant area index (PAI, including stems and branches) are monitored on a 10 day basis along a 1 km transect.

The four components (incoming and outgoing short- and longwave) of the radiation budget were measured with a CNR1 (Kipp and Zonen, Delft, Holland) at the four sites and calibration was checked in 2006. Additional radiation data were collected in September 2008 to document bare soil albedo variability. Volumetric soil water content was monitored with CS616 reflectometers