Proceedings of H01, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013 (IAHS Publ. 359, 2013).

Field and simulation experiments for investigating regional land–atmosphere interactions in West Africa: experimental set-up and first results

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Abstract West Africa is characterized by strong land surface changes due to various anthropogenic activities which influence the spatiotemporal patterns of hydro-meteorological fluxes and which might alter the availability of water resources. To investigate these questions, we use a novel two-way coupled atmospheric–hydrological model that allows for a consistent and dynamic simulation of regional land–atmosphere interactions in mesoscale river basins. This model is adapted stepwise for the West African Sudanian Savannah, focusing on a main tributary of the White Volta. In addition, the experimental set-up of three micro-meteorological stations using the eddy covariance technique is illustrated; they have been recently established in this region along a gradient of increasing agricultural activity. First measurements and simulation outcomes from the adaption of the atmospheric model are promising, but further model adaptation is crucial for a reliable simulation of surface fluxes on a daily or finer temporal scale.

Key words land–atmosphere interactions; coupled atmospheric–hydrological simulations; Weather Research and Forecasting model; land surface model; eddy covariance stations; hydro-meteorological fluxes; precipitation; West Africa

INTRODUCTION

Over the last few decades the land surface in West Africa has been heavily changed due to various anthropogenic activities. The impacts of these land surface changes in conjunction with climate change on hydro-meteorological fluxes are uncertain, hindering the development of valuable adaptation measures for a sustainable management of water and other natural resources. A central problem is that exchange processes and feedback mechanisms between components of the land surface and the overlying atmosphere are not well understood. To refine our understanding of land–atmosphere interactions, energy and water fluxes derived from micro-meteorological stations based on the eddy covariance (EC) technique can be used. In past decades, EC stations have been established in many geographical regions of the world to measure energy and water fluxes, and further variables, in various terrestrial ecosystems (Baldochi, 2001; FluxNet, 2012). One of the earliest EC experiments was made in West Africa in August 1992 at a field site in the Sudanian Savannah in southern Niger during the transition period from the wet to the dry season (Verhoef *et al*., 1996). Another attempt was performed at a site in Nigeria by Jegede *et al*. (2004) in February and March 2004. The heat fluxes were analysed for three typical weather situations by Mauder *et al*. (2007). Since these first activities, a number of further sites have been equipped with EC stations in West Africa, providing continuous flux measurements over several years in various land cover types (FluxNet, 2012).

A further challenge is an enhancement of current techniques used in regional land-use change and regional climate-change simulation experiments, which still bear considerable limitations. Land surface schemes in atmospheric models simulate water and energy transfer between the land surface and the overlying atmosphere. The partitioning of precipitation into evapotranspiration and runoff, and of the incoming radiation into latent and sensible and soil heat fluxes, is controlled by bio-geophysical parameters describing specific characteristics of the land surface. To study the impact of climate change on water resources in mesoscale and small-scale hydrological catchments, a common strategy is to use meteorological simulations of a regional climate model as input for a distributed process-oriented hydrological model. An example for West Africa is given by Wagner *et al.* (2006). However, a consistent simulation of land–atmosphere interactions using this approach is not possible because no feedback mechanisms are considered between a hydrological and an atmospheric model. To tackle this problem, a new land surface model with an additional representation of hydrological processes has been developed by Gochis *et al*. (2010), which can be coupled in a feedback mode with the Weather and Research Forecasting model (WRF; Skamarock *et al*., 2008). Rummler (2011) tested this approach for a small-scale river basin in southern Germany. A further strategy is an improvement of the spatiotemporal representation of key bio-geophysical parameters of the land surface by using remote sensing information (Sandholt *et al*., 2003; Wagner *et al*., 2009). Remote sensing information is also used as a source of information for validation of atmospheric or hydrological simulations. For instance, Saux-Picart *et al.* (2009) used soil moisture observations and land surface temperature from satellite images for a validation of a distributed land surface model applied for a mesoscale terrain in the Niger basin.

Because a number of micro-meteorological stations have been established in many geographical regions of the world, the use of EC measurements for evaluation of the performance of land surface models has received more and more attention. Recently, Decker *et al.* (2012) used latent and sensible heat measurements from EC stations located in the Northern Hemisphere for an evaluation of four current global re-analysis products. So far, there seems to be only one investigation that has used measurements from an EC station in West Africa for an evaluation of land surface model simulations. This study was performed by Grote *et al.* (2009) for a near-natural savannah site located in the national reserve in southwest Burkina Faso.

The objective of this study is to present current field and simulation experiments for an investigation of regional land–atmosphere interactions in a semi-arid region in West Africa located in the Sudanian savannah belt of Burkina Faso and Ghana. Recently, three EC stations have been established in this region to perform continuous measurements of energy, water vapour and carbon dioxide fluxes along a transect of increasing agricultural activity. In this paper, a brief overview of the experimental set-up of these EC sites is given and the first measurements are presented. In addition, the basic experimental set-up for a consistent simulation of regional land–atmosphere interactions within a mesoscale river basin is illustrated using the two-way coupled atmospheric–hydrological model selected by Rummler (2011). The first step of the model development is a stepwise adaptation of the parameterization of the atmospheric and hydrological model for the target region. Initial outcomes of the adaptation of the atmospheric model are illustrated in this paper with a special focus on a simulation of daily precipitation characteristics.

EXPERIMENTAL SET-UP OF MICRO-METEOROLOGICAL MEASUREMENTS

Due to the enormous population growth in West Africa, many areas of the Sudanian savannah have been converted to farmland because the majority of people are living directly or indirectly on the income produced by agriculture. The dominant farming form is subsistence farming. In particular, the Upper East Region in North Ghana is one of the most populous areas in the Sudanian savannah belt and is intensively-used for agriculture. Around 100 km northwestwards from this region is the national reserve, Nazinga Park, situated in south Burkina Faso.

The size of the national reserve is around 940 km^2, including a core protection zone where no farming activities are allowed. Along this gradient of increasing agricultural activity, three EC stations have been established. The EC stations are located close to the Ghanaian–Burkinabe border (Fig. 1). The first EC site (10.841°N, 0.918°W) is located northwest of Bolgatanga in north Ghana next to the village of Sumbrungu Agusi. This site represents a highly degraded site with intensive agricultural activities. The area surrounding the EC station (<200 m) is mostly used as rangeland for livestock (see Fig. 2). The second EC station is located (11.152°N, 1.586°W) in the Nazinga Park. The Nazinga site should represent a near-natural Sudanian savannah site with

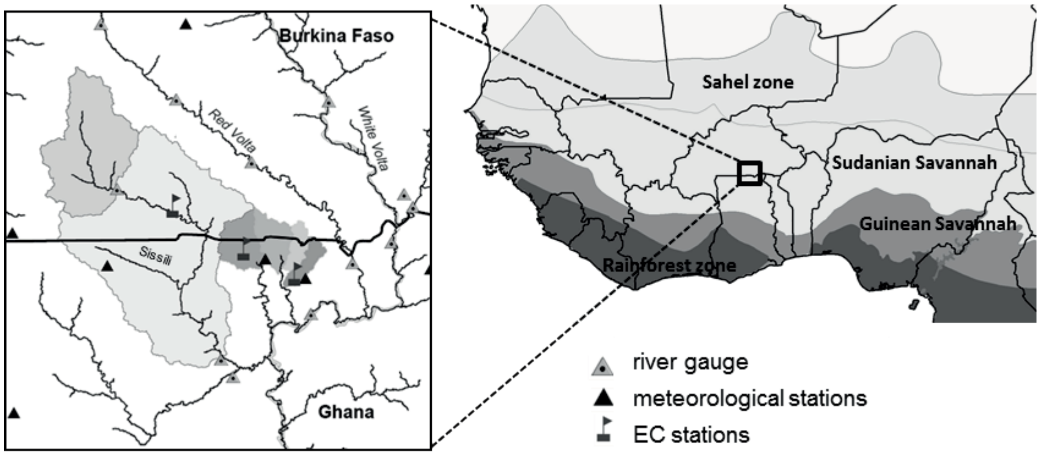

Fig. 1 Recently established EC sites located in the Sudanian Savannah belt in South Burkina Faso and North Ghana. The shaded areas in the left figure show the river basin of interest, the Sissili basin, and its neighbouring catchments.

no agricultural activities. The third EC site (10.918°N, 1.319°W) is located between the Sumbrungu and Nazinga sites, next to the village Kayoro in a less populated area which is partially used for agriculture. This site should represent a mixture between the Sumbrungu site and the Nazinga site with a more near-to-nature agricultural management. The configuration of the measurement equipment for the Sumbrungu site is given in Fig. 2. At each site the same measurement equipment is used, but with varying measuring height depending on the mean vegetation height. The measurement equipment consists of a sonic anemometer to measure a three-dimensional wind field. Water vapour content and carbon dioxide content of the atmosphere is determined using an open path gas analyser. A pair of pyranometers and a pair of pyrgeometers is used to determine net radiation of incoming and surface-reflected outgoing shortwave and long-wave radiation. Relative air humidity and air temperature are measured using a single probe protected by a ventilated radiation shield. Ground heat flux measurements are made based on self-calibrating heat flux plates. In addition, the soil temperature is recorded at three depths and the soil moisture above the heat flux plates is recorded. A weighing gauge and tipping-bucket system are used for precipitation measurements, and a further compact weather station has been installed for additional records and backup of standard variables. Additionally, a camera is used to observe the phenology of the vegetation. The measurements are currently made with a frequency of 20 Hz. The eddy covariance analysis is performed on-site on a daily basis using the statistical software package TK3 (Mauder & Foken, 2011), which includes a variety of statistical correction

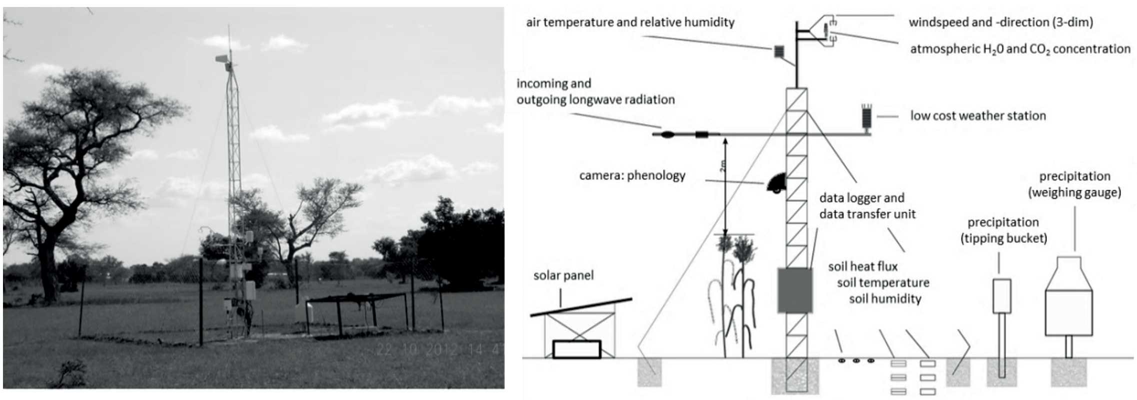

Fig. 2. The EC station at Sumbrungu with an overview about the measurement equipment. The picture was taken after the installation in October 2012.

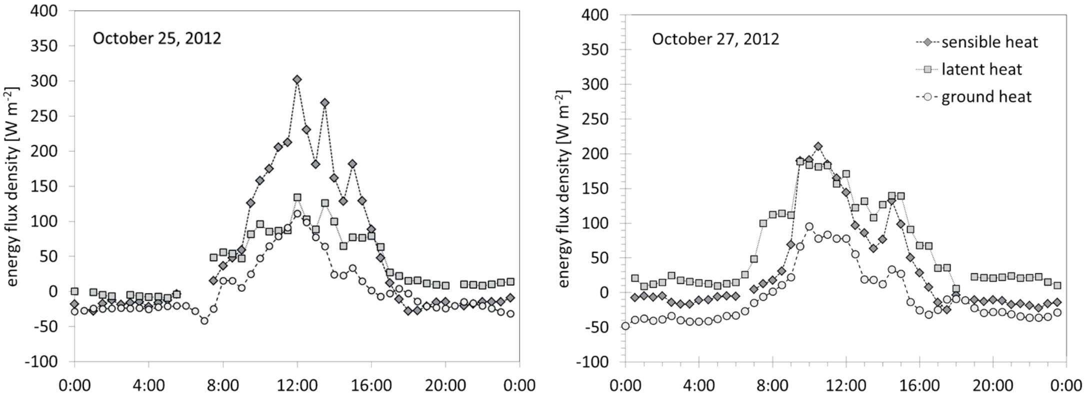

Fig. 3 Diurnal variation of sensible and latent heat fluxes before and after a rainy day.

techniques for refinement of the measurements. The high frequency measurements are aggregated to half-hourly measurements and transferred online to a data server. An example of the heat fluxes at the Kayoro site is given in Fig. 3 in October 2012 showing a moderate increase of latent heat fluxes after a day (26 October 2012) with a moderate rainfall event (11.4 mm).

EXPERIMENTAL SET-UP AND STEPWISE ADAPTATION OF THE ATMOSPHERIC–HYDROLOGICAL MODEL

The atmospheric–hydrological model consists of the Weather and Research Forecasting (WRF, Skamarock *et al.*, 2008) model and the Distributed Hydrological Modeling Systems of the US National Centre for Atmospheric Research (NDHMS; Gochis *et al.*, 2010). The previous version of WRF, the Fifth-Generation Meso-Scale Model (MM5, Grell *et al.*, 1994) has been used in several regional climate changes studies in West Africa (Jung & Kunstmann, 2007; Jung *et al.*, 2012). A current review about regional climate modelling applications is provided by Paeth *et al.* (2011) with a special focus on West Africa. The NDHMS belongs to the group of distributed process-oriented hydrological models. In comparison to current land surface models used in WRF, such as the Noah land surface model (Chen & Dudhia, 2001), the NDHMS includes sophisticated process formulations for runoff concentration and channel routing to describe how surface and subsurface water is transferred to the outlet of a river basin. The vertical water and energy transfer between the components of the land surface is simulated within the NDHMS using the Noah land surface model. A more detailed description of the two-way coupled atmospheric–hydrological model is given by Rummler (2011).

The two-way coupled atmospheric–hydrological simulations are performed using large-scale atmospheric information from the ERA-Interim re-analysis archive (Dee *et al.*, 2011) generated by an atmospheric general circulation model (AGCM). The domain for the coupled atmospheric–hydrological simulation is illustrated in Fig. 4. The AGCM information is transferred stepwise from a horizontal resolution of approx. 80 km to a final resolution of 2.5 km based on three domains. The domain configuration is primarily a compromise between the outcomes of former investigations using MM5 (Jung & Kunstmann, 2007; Jung *et al.*, 2012), the objective to capture major atmospheric drivers such as the African Easterly Waves, and available computing resources. The river basin of interest, the Sissili basin, is in the centre of the inner domain. The Sissili is a less-regulated main tributary of the White Volta flowing through the Nazinga Park. In contrast to other White Volta tributaries, the water level of the Sissili is recorded on a daily basis at two gauges. This has the advantage that daily discharge observations can be used for a validation of the NDHMS.

High resolution atmospheric–hydrological simulations in a feedback mode are computationally demanding. Before this type of simulation is performed, uncoupled hydrological and atmospheric simulations are carried out based on observational and (or) re-analysis information. In

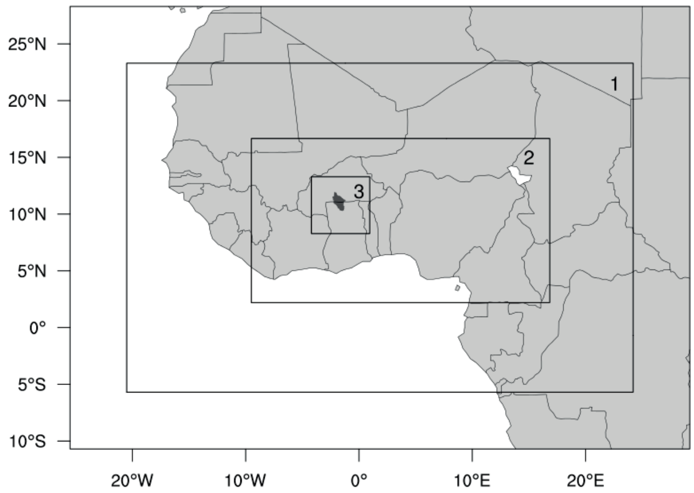

Fig. 4 The current domain configuration of the atmospheric-hydrological model applied for a semi-arid region in West Africa. The catchment area of the Sissili basin is highlighted in the centre of domain 3.

a first step, WRF simulations in a lower resolution using domain 1 and 2 are performed for the rainy season of a dry year (1982) and a wet year (1999) to identify an optimum model configuration for simulation of surface fluxes. In each simulation run, the set of parameterization schemes is modified without changing the further model set-up. The outcomes of this iterative procedure are listed in Table 1 for the rainy phase in 1999, illustrating a tremendous influence on the simulated precipitation amount. The adaptation can strongly reduce the overestimation from 432 mm (2.4 mm/d) to 162 mm (0.9 mm/d) relative to a WRF simulation using a standard configuration.

In this example the simulated precipitation is compared to more than 70 daily point observations from weather and rainfalls stations located in Burkina Faso and Ghana. However, even for a quasi-unbiased precipitation simulation, the simulation of daily precipitation characteristics using the current WRF model configuration is poor in comparison to point observations. For instance, Fig. 5 shows the difference between the simulated and the observed monthly precipitation amount at the rainfall station in Ouahigouya (Burkina Faso) for 1982. WRF meets the general characteristics of the monthly precipitation regime. However, a comparison of the simulated and the observed number of wet days ($P > 2$ mm/d) per months still shows tremendous deficiencies, in particular for June, July and August when the number of wet days is clearly overestimated.

Table 1 Systematic differences (bias) between mean observed and mean simulated daily precipitation of more than 70 locations in Ghana and Burkina Faso. In each WRF run a different set of parameterization approaches is selected; rainy season 1999.

WRF run	LS	MP	CU	PBL	SLR	SL	Bias (mm/d)
Standard	Noah	WSM3	KF	YSU	RD	MM5	2.9
2	Noah	WSM3	GD3D	YSU	RRTMG	MM5	5.3
3	Noah	THM	GD3D	YSU	RRTMG	MM5	4.9
4	Noah	WSM5	BMJ	YSU	RRTMG	MM5	1.3
5	Noah	WSM5	SAS	YSU	RRTMG	MM5	1.7
6	Noah	WSM5	BMJ	MYJ	RRTMG	ETA	0.9
7	Noah	WSM5	GD3D	MYJ	RRTMG	ETA	3.2

LS, land surface; MP, microphysics; CU, cumulus; PBL, planetary boundary layer; SLR, shortwave and longwave radiation; SL, surface layer; Noah, Noah LSM; THM, Thompson; KF, Kain-Fritsch; GR3D, Grell-Devenyi; BMJ, Betts-Miller-Janjic ; SAS, New Simplified Arakawa Schubert scheme; YSU, Yonsei State University; MYJ, Mellor-Yamada-Janjic; RRTMG ,Rapid Radiative Transfer Model; RD, Rapid Radiative Transfer Model and Dudhia; MM5, MM5Monin-Obukov; ETA, Monin-Obukov (Janjic) scheme, after WRF Version 3.4

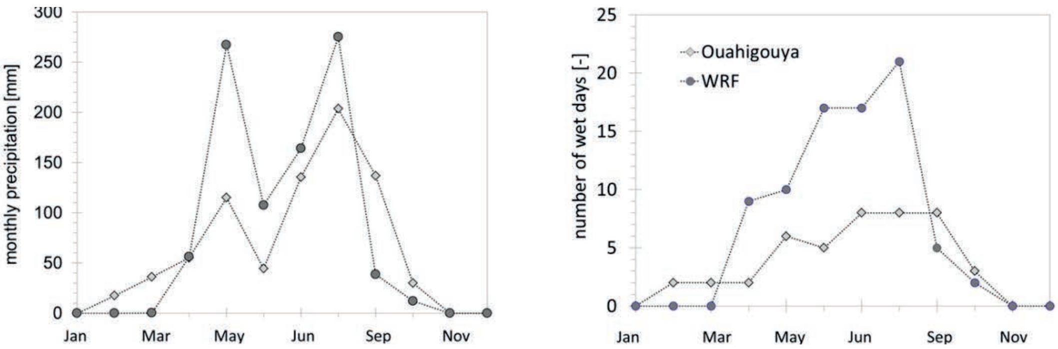

Fig. 5 Simulated precipitation amount and number of wet days for 1982 in comparison to point observations of the rainfall station in Ouahigouya, Burkina Faso. The simulated precipitation of the nearest grid point is selected for a comparison.

CONCLUSIONS AND OUTLOOK

Three micro-meteorological stations using an eddy covariance technique have been established in the Sudanian savannah in southern Burkina Faso and northern Ghana to provide continuous measurements of energy and water fluxes along a transect of increasing agricultural activity. In future, this information will be used for an additional evaluation of surface fluxes simulated by the coupled atmospheric–hydrological models presented in this study. A stepwise adaptation of the atmospheric model reduced significantly an overestimation of the precipitation amount for the rainy season in 1999. However, further advancement and evaluation of the atmospheric model is crucial to improve the current deficiencies, as illustrated for daily precipitation characteristics at a specific location. In future, remote sensing information will be used as additional information to improve the description of the bio-geophysical land surface parameters within the atmospheric–hydrological model. A preliminary investigation regarding this issue that includes an inter-comparison of regional and global available land cover types for West Africa was performed by Gessner *et al*. (2012).

Acknowledgements The study is part of the core research programme of the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) funded by the German Ministry of Education and Research. The authors would like to thank our national and international partners within WASCAL, in particular Samuel Guug, Igor Bado, Ahmed Balogun and Emmanuel C. Okogbue for the comprehensive help before, during and after the installation of the EC stations. We also acknowledge the national weather services of Burkina Faso and Ghana for providing daily precipitation observations. The precipitation data was provided during the GLOWA-Volta project. Special thanks also to an anonymous reviewer for the valuable comments.

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