



Combined analysis of energy and water balances to estimate latent heat flux of a sudanian small catchment

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SUMMARY

Actual evapotranspiration is one of the major components of both energy and water budgets, but is often difficult to monitor over long period with sufficient accuracy. Within the framework of the “AMMA-CATCH” program, a project dedicated to the study of the West African Monsoon, a large aperture scintillometer has been installed in a small catchment (12 km²), located in the North of Benin, a region exposed to sudanian climate. The present study is an attempt to estimate the latent heat flux over this small but heterogeneous catchment based on scintillation and ground observations. The analysis covers the end of the dry season (lasting from February to April 2006). During this period two isolated rainfall events occurred, giving a unique opportunity to study energy and water budgets simultaneously.

The comparison between the average sensible heat flux derived from scintillometer observations and the one obtained with conventional eddy correlation shows a relatively good agreement, where the scattering is mainly explained by differences in footprint associated with both instruments. A relevant hourly residual latent heat flux is then obtained through the energy balance equation, with careful attention brought to the net radiation, and the ground heat fluxes. The residual of the energy budget equation is compared to soil water losses from vadose zone and water table, in order to evaluate whether this estimation is consistent with the water budget of the ground. Daily soil water depletion within the first meter of the surface shows a similar dynamic as the one calculated from the energy balance equation, but exhibits a constant 1 mm/day lag. The excess of actual evapotranspiration is supposed to be explained by water table losses and root extraction by trees. Finally, this study shows how combined energy and water budget analysis can help to better understand water transfers at the watershed scale.

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Introduction

Actual evapotranspiration (AET) is one of the key factors of land/atmosphere interactions. Apart from the incoming radiation, AET is the most important component of the energy budget at the surface when sufficient water is available. Under sudanian climate, this term can reach up to 70% of the surface energy balance (SEB) during the wet season, whereas it drops to less than 20% during the dry season (Bagayoko et al., 2007; Schuttemeyer et al., 2006). It is also one of the most important components of the water budget. Precipitation 30–70% (depending on the season) returns to the atmosphere through evapotranspiration (Brabant, 1998). Moreover different hydrological and Soil Vegetation Atmosphere Transfer (SVAT) models produce, for a given situation, a wide range of AET estimations (Lohmann et al., 1998; Varado et al., 2006; Le Lay, 2006). These results show the important uncertainty associ-

ated with this water budget component and our inability to validate evapotranspiration parameterization in models induced by the lack of AET observations (Lohmann and Wood, 2003).

Our understanding of continental surface behaviour is then reduced to our capacity to monitor AET. This is particularly true in the context of the AMMA program (African Monsoon Multidisciplinary Analyses¹ which aims to improve our knowledge of the interactions between continental surfaces and monsoon processes in West Africa (Lebel et al., 2009). To explore those interactions, a special effort has been given to measure turbulent fluxes from Lat 9°N to Lat 17°N. Studies within this issue propose the first results from the AMMA flux network under sahelian and sudanian climate. Readers can refer to Ramier et al. (2009), Timouk et al. (2009) and Ezzahar et al. (2009) for the sahelian part.

However very few effective measurement techniques are available to monitor AET. For the study of the boundary layer, recent progress in eddy correlation instrumentation and data analysis allows closure of the energy budget from direct measurements over

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¹ <http://www.ammainternational.org>.

homogeneous surface (Heusinkveld et al., 2004; Mauder et al., 2006). Nevertheless, these methods often failed at providing accurate turbulent fluxes to close the surface energy balance (SEB), since horizontal energy transfers are involved in the budget (Foken et al., 2006). Moreover, they are considered as local measurements (a few hundreds of m²) and cannot be extended to surrounding areas, even for apparent homogeneous vegetation cover (Foken et al., 2006; Katul et al., 1999). Indeed, heterogeneous vegetation cover, heterogeneous geological context and/or complex topography produce a large AET variability due to the complexity of the processes involved in the water transfer from soil through vegetation to atmospheric boundary layer. Thus, at watershed scale, standard methods that necessitate only standard meteorological entries, like the Penmann–Monteith (Allen et al., 1998), are often used despite the strong assumptions involved.

From an hydrological point of view, the catchment is the relevant scale, because it integrates all the hydrological processes in a closed area. Hydrological models usually simulate water discharge, giving a rain input. Then, a part of the water budget residual can be interpreted as an AET. However, the closure of the water budget can only be confirmed if the different contributions are monitored at this scale. Nevertheless, some water components like AET, precipitation rate, infiltration and deep percolation are often only locally documented. This leads to large uncertainties in prediction of those fluxes, even if the river discharge outflow is well simulated (Le Lay et al., 2008) and uncertainties on water transfer processes involved. For all these reasons, integrated AET measurements are highly requested for atmospheric and hydrological studies.

Recent scintillometric instruments have been developed to measure turbulent fluxes over several km². Scintillometers provide a measurement of the fluctuation of the refractive index of the air along the path between a transmitter and a receiver. This is related to the fluctuation of thermodynamic parameters, mainly air temperature and humidity, induced by turbulent eddies. An average sensible heat flux (H) over several km² can be derived from infra red large aperture scintillometer (LAS) measurements (Hill et al., 1992; De Bruin et al., 1993) whereas an average AET can be derived from microwave scintillometer (MWS) measurements (Kohsiek and Herben, 1983; Green et al., 2000; Meijninger et al., 2002a). The latest remains at research state, and is not ready to be used for long term experiment at present.

LAS was also proven to be effective for different terrain configurations such as complex topography (Chehbouni et al., 2000; Lagouarde et al., 2006) or heterogeneous vegetation cover (Meijninger et al., 2002b). An extra validation study is proposed over patchy sahelian crop cover (Ezzahar et al., 2009). More recently, it has been shown that LAS makes possible the evaluation of latent heat flux combined with an energy budget calculation (Schuttemeyer et al., 2006). All these studies have contributed to make LAS an operational technology.

Following Meijninger et al. (2002b) and more recently Schuttemeyer et al. (2006), we have deployed a LAS over a small catchment (12 km²) to derive latent heat flux series from the residual term of the SEB equation. This catchment is located in North Benin, a region exposed to soudano-sahelian climate. This area is covered by a mixture of shrublands, various woodlands and crops/or bare soils. As no mechanical materials are available for agriculture, the landscape is composed of small fields typically less than 1 ha in area. This heterogeneity makes direct measurements of AET very difficult at the patch scale because the footprints associated with the sensors cover a constantly changing area of vegetation type. The validation approach proposed by Meijninger et al. (2002b), which consists of the comparison of the integrated LAS measurements with an aggregated estimation from measurements at patch scale, is then difficult to apply in such a context. This study evalu-

ates the suitability of a LAS method to estimate hourly latent heat flux over a very heterogeneous area, by the simultaneous evaluation of energy budgets and water budgets, for a composite area (some km²) during the dry season in North Benin.

The first part of this paper presents the experimental site, and the data available for this study. Theory and methods used to derive aggregated energy fluxes are developed in second and third parts. The fourth section discusses hourly values of fluxes to get confidence in the various fluxes that enter the determination of the area-averaged $\langle \text{AET} \rangle$. One could consider this $\langle \text{AET} \rangle$ as the output of “validation of the various methods on hourly basis”. Then the last section uses aggregated daily averages $\langle \text{AET} \rangle_{24}$ to understand the water balance of the catchment. It also presents the case of an hydrological response to a rainy event for a small watershed.

Region of interest and data set

The AMMA program aims at improving our knowledge of the West African Monsoon, which is the most important climatic feature in West Africa. The main objectives of this international programme are to improve our understanding of the physical processes associated with different phases of the monsoon: “the genesis, the intensification and the decline of the monsoon fluxes”, and to explore the combined interactions between the meteorological and the surface scales in the production of rainfall (Redelsperger et al., 2006).

The ARA watershed is a 12 km² basin, part of the Donga catchment (586 km²), in the Northern part of Benin (Lat 9.74°N, Long 1.60°E). It represents a typical cultivated area under sudanian climate. Fig. 1a presents a general view of the catchment as well as the location of the main sensors. A vegetation classification is also proposed and mapped into three main vegetation types: woodland, shrubland and crops. Woodland and shrubland are composed of herbaceous and woody layers, the last one comes denser and denser in a continuum from grassland to woodland. In this study we only consider two classes: shrublands where the woody vegetation does not exceed 2 m high and woodlands where most trees do not exceed 5 m. Both of these vegetation covers are sparse as can be observed in Fig. 3. The global map in Fig. 1a shows a simplified classification based on vegetation height: bare soil (30%), shrubland (25%) and woodland (45%), mainly on elevated areas. In the actual basin the relative proportion of herbaceous and woody layers is continuous, as well as the height of the trees (Fig. 3) thus additional vegetation classes could be defined, mainly during the rainy season when annual vegetation has grown. The strongest seasonal variability comes from the herbaceous cycle during the wet season. At the end of the wet season, farmers burn all the herbaceous vegetation, even in the natural areas (shrubland or woodland). Crop areas return to bare soil until a new seeding at the beginning of the wet season. This study focuses on dry season conditions. All crop areas are reduced to bare soils and no herbaceous cover is present between the trees in the shrublands and woodlands. During this period most of the shrubs and trees keep their leaves.

Experimental setup

The ARA watershed is one of the observation ‘super sites’ in the AMMA field campaign framework. The AMMA International Implementation plan² gives details on the strategy and modus operandi on the Ouémé meso-scale site.³ Many sensors (see Fig. 1a) are deployed in order to monitor the different hydrological terms. Two rain

² <http://amma-international.org/implementation/docs/icigdocs/index>.

³ <http://amma-international.org/implementation/docs/TT5.pdf>.

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