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Hydrological modelling and associated microwave emission of a semi-arid region in South-western Niger

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SUMMARY

Studying surface–atmosphere feedback is often limited by the accuracy of the land surface observations (particularly soil moisture estimates) or the performance of the land surface models. To further our understanding of soil moisture effects on land–atmosphere fluxes, improvements in soil moisture mapping over large regions are necessary. The aim of this study was to obtain accurate soil moisture mapping over a 120 by 100 km^2 area in West Africa using the considerable amount of measurements available from local and regional scales, recorded during the African monsoon multidisciplinary analysis (AMMA) experiment. The modelling strategy was based on the use of a land surface model (LSM), employed to provide high-resolution soil moisture mapping over the studied area. A microwave emission model was then used to simulate associated microwave brightness temperatures (TB) to compare with the Advanced microwave scanning radiometer (AMSR) at the same spatial (25 by 20 km^2) and temporal resolution (daily). Discrepancies between observed and simulated TB were analysed and used to calibrate the LSM and the microwave emission models to match the specific hydrology and soil microwave behaviour of the studied area. Nevertheless, a positive bias of the near-surface soil moisture remained and the land surface model was still unable to reproduce the rapid dynamic of the near-surface soil moisture observed at the local and regional scales in this climatic context. To solve this problem, a secondary surface soil layer was added to match in situ soil moisture measurements as well as satellite microwave measurements. Additionally, the choice of the soil permittivity model was found to be of prior importance in order to perform suitable microwave brightness temperatures. Finally, a soil moisture retrieval algorithm based on AMSR and meteosat second generation (MSG) measurements was proposed in order to improve the quality of the soil moisture estimates over the studied area (the root mean square error decreases from 5.4 % vol. to 2.8 % vol).

Introduction

In West Africa, surface boundary conditions play an important role in initiation and maintenance of the West-African monsoon system. The most important surface boundary conditions are sea surface temperature, surface soil moisture, and soil temperature. The influence of the land surface wetness on convection and precipitation has been studied at the global scale (Guo et al., 2006; Koster et al., 2004, 2006) and at the regional scale in the United States (Beljaars et al., 1996) and in India (Douville et al., 2001). In West Africa, surface-vegetation-atmosphere feedbacks were studied by various authors (Taylor and Ellis, 2006; Taylor et al., 2007; Charney et al., 1975; Brovkin et al., 1998; Wang and Eltahir, 2000; Zeng et al., 1999) and are based on observations or model analysis.

To further our understanding of soil moisture effects on land–atmosphere fluxes in West Africa, improvements in soil moisture mapping are necessary. In the past decade, significant improvements have been made in remote sensing techniques used to retrieve soil moisture from satellite-based sensors, and new sensors have been developed. In the near future, two proposed space missions will be exclusively devoted to measure soil moisture from space; the SMOS mission (Kerr et al., 2001) and the SMAP mission (Entekhabi et al., 2007). Significant improvements in soil moisture mapping were also achieved using assimilation techniques, which are designed to merge remote sensing retrievals with information provided by a land surface model (LSM). Used in isolation, a land surface model driven with observed

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meteorological forcing and land surface data may be subject to errors due to incorrect weather forcing, model parameter uncertainty, and incorrect land surface model formulation. Alternatively, soil moisture retrievals based on indirect measurements from satellite sensors may be subject to errors due to instrumental noise, uncertainty of the retrieval formulation, and retrieval algorithm parameterization. Assimilation techniques take advantage of both data and models to find an optimal solution that minimizes errors related to the land surface model and the errors in remotely sensed retrievals (Reichle et al., 2008).

Prior to testing an assimilation scheme throughout West Africa, the objective of this study was to evaluate a land surface model coupled with a microwave emission model over a 120 by 100 km^2 region in West Africa. The methodology was to produce simulated soil moisture maps and associated microwave brightness temperature maps and to compare them with local ground-based measurements and regional satellite-based measurements. Discrepancies between observations and simulations were used to calibrate the LSM model and the microwave emission model to the specific hydrological processes and soil microwave behaviour of the studied area.

The study was based on the significant amount of in situ land surface and atmospheric measurements collected during the AMMA experiment (Redelsperger et al., 2006). The recent Advanced Microwave Scanning Radiometer (AMSR) on Aqua provided microwave measurements. As these products are known to be of limited value in heavily vegetated regions (Jackson et al., 2008), the Sahel region in West Africa, ranging from 10°N to 20°N, provided an excellent opportunity to evaluate AMSR products because much of the region has relatively sparse vegetation. Additionally, the AMSR products have been widely assessed in the United States (Bindlish et al., 2006; Jackson et al., 2005; McCabe et al., 2005) and in Europe (Rüdiger et al., 2008), but only few studies have been devoted to West Africa (Gruhier et al., 2008).

The modelling strategy was two-part. First, in-situ land surface and atmospheric measurements were used with the ISBA (Noilhan and Planton, 1989) land surface model of Météo-France to provide accurate water and energy simulations at the local scale. Second, a microwave emission model was used to simulate brightness temperatures at the AMSR-E spatial and temporal resolution. The studied area and the data are described in ''Experimental domain and data''. An overview of the ISBA LSM and details of the microwave emission model are presented in ''Models'' Results at both the local and the regional scales are given in ''Results'', while the main conclusions of this study are discussed in ''Conclusions''.

Experimental domain and data

Studied area

The studied area is a 120 by 100 km^2 region located in Southwestern Niger (1.6–3.1°E; 13–14°N). The annual rainfall ranges from 400 to 650 mm with strong variability within the area. A recording rain gauge network continuously operated over this area since 1990 was part of the EPSAT-Niger long term monitoring program (Lebel et al., 1992). Based on 31 rain gauge stations (i.e. more than one station every 20 km, see Fig. 1), a kriging procedure (see Ali et al. (2005)) for the methodology) was used to provide a ground-based rainfall product at a 5×5 km^2 spatial resolution every 15 min throughout 2006. Statistical studies were done over a 100 by 100 km^2 area by Balme et al. (2006), and stated that a single rain gauge station provides 30% error on the annual cumulative rainfall estimate. To remain below a 5% error threshold, the number of stations should be greater than 8. At a higher timescale, the authors showed that the rainfall estimation error decreases from 113% to 21% at the event scale when the number of stations increases from 1 to 12. Vischel et al. (2009) showed that stochastic conditioned simulations provide a much more realistic spectrum of possible rain fields that simple kriged rain fields.

Soil moisture and soil temperature measurements were made at three sites (Wankama, Banizoumbou, Tondikiboro) within a 15×15 km^2 area east of Niamey (Fig. 1). A general description of the three sites is available in Cappelaere et al. (2009). The distance between Wankama and Banizoumbou is 13 km, and the distance between Tondikiboro and Banizoumbou is 5 km. Concerning surface soil moisture measurements, two sensors were installed horizontally at 5 cm depth in June 2006 at each of the three sites in fallow land cover. Additional soil moisture and temperature profile measurements were installed in 2005 at the Wankama site in fallow and millet land-covers respectively, using vertically installed sensors (10–40 cm; 40–70 cm; 70–100 cm; 130–160 cm) (Descroix et al., 2009). In addition, surface runoff measurements were obtained at different spatial scales from 10 to 300,000 m^2. Flux measurements were obtained by eddy correlation over fallow and millet land-cover (Ramier et al., 2009). Finally, atmospheric measurements (air humidity, air temperature, wind speed, pressure, long and short wave radiation) were archived every 15 min over the Banizoumbou site.

Hydrological processes in semi-arid regions have been widely studied during the last decades. The Hapex–Sahel experiment was one such important research effort (Cappelaere et al., 2003; Peugeot et al., 1997). The data collected during the Hapex–Sahel experiment have shown the major role played by soil crusting on runoff generation in the Niamey region in the Sahel. At the point scale (1 m^2 plot), runoff coefficients (runoff divided by rainfall) range from 0.39 to 0.56 (Esteves and Lapetite, 2003). Similar results were obtained during the AMMA field campaign where runoff coefficients were measured over different soil types. During the 2006 rainy season (about 20 rainfall events), runoff coefficients measured over a 10 m^2 area range from 0.02 to 0.85 (mean value 0.44) over bare crusted soil, and from 0.02 to 0.54 (mean value 0.15) over fallow soil (Descroix et al., submitted for publication). At this scale, infiltration and runoff are mainly driven by the hydraulic properties of the crust.

Advanced microwave scanning radiometer (AMSR)

The AMSR (advanced microwave scanning radiometer) radiometer onboard the AQUA satellite, operated by the NASA, has been regularly acquiring data since June 2002 (Njoku et al., 2003; Njoku, 2004). The instrument operates at two low frequencies (6.9 GHz C-band and 10.7 GHz X-band) and three higher frequencies (18.9, 36.8, 89.0 GHz). Measurements are obtained for two polarizations and a single incidence angle of 55° at the surface. At C and X-band, the spatial resolution is 55 km at approximately 1:30 and 13:30 local time for descending and ascending tracks respectively. Due to overlapping (55 km scene measurements are recorded at equal intervals of 10 km), a level-3 product is available at a higher spatial resolution of 25×20 km^2 in a regular lat–lon grid. The temporal resolution ranges from 12 to 36 h. Passive microwave measurements at frequencies from 1 to 10 GHz are known to be strongly related to the soil dielectric constant, which is physically related to soil moisture. At these frequencies, the main part of the emission signal comes from soil moisture, vegetation water content, soil temperature, and soil roughness effects.

In situ soil moisture and calibration procedure

In situ soil moisture measurements were obtained using CS616 sensors (Campbell Scientific Inc., Logan, Utah, USA). CS616's output is a period, measured in μs, and the use of a calibration curve is required to transform these measurements into volumetric soil