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How satellite rainfall estimate errors may impact rainfed cereal yield simulation in West Africa

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ABSTRACT

Rainfall monitoring via satellite sensors is particularly relevant for the agricultural sector of West Africa. Indeed, food shortages in this region are often caused by rainfall deficits and an early access to data available for the entire region can help to provide credible and timely information for better decision making. This study assesses the accuracy of state-of-the-art satellite rainfall retrievals for agriculture applications in two sites in Niger and Benin. Although these satellite data are widely used instead of rain gauge data for such applications, we found that, in a crop-modelling framework, their use can introduce large biases in crop yield simulations. Biases differ strongly among the four cultivars considered in both sites and are not simple extrapolation of each satellite product cumulative rainfall amount biases. In particular, we found that if an accurate estimation of the annual cumulative rainfall amount is important for yield simulations of pearl millet 'Souna 3' and 'Somno' cultivars in Niger, a realistic distribution of rainfall is also very important for predicting pearl millet 'Somno' and 'HK' yields in Niger as well as maize yields in Benin. Overall the satellite products tested, 3B42v6 appears to be the most suitable satellite product for our specific agricultural application since it minimizes both biases in rainfall distribution and in annual cumulative rainfall amount. For each crop and in both regions, biases in crop yield prediction are the highest when using non-calibrated satellite rainfall products (PERSIANN, 3B42RT, CMORPH and GSMAP).

1. Introduction

Monitoring climate-related hazards is considered as one of the highest priorities of the National Adaptation Programmes of Action of least developed countries, particularly in West Africa. In this region, recurrent droughts and associated famines in the late 1970s and early 1980s led national authorities and the international community to coordinate efforts to limit the impact of drought through the establishment of early warning systems (EWS; Genesio et al., 2011) aiming at providing credible and timely information for better intervention decision-making. In this context, rainfall monitoring via sensors from satellites is highly relevant to such drought-focused EWS. Indeed, it presents two significant advantages over conventional ground based observation approaches: (i) prompt data availability and (ii) complete area coverage irrespective of terrain. Indeed, the rain gauge network is too sparse in many regions of West Africa to allow precise and timely estimates of the spatial pattern of precipitation at local and regional scales. Furthermore, a new generation of precipitation products combining infrared and microwaves measurements (Xie and Arkin, 1996; Hsu et al., 1997; Sorooshian et al., 2000; Huffman et al., 2001; Joyce et al., 2004; Huffman et al., 2007; Bergès et al., 2010) benefits from the good sampling rate of IR measurements from geostationary earth orbiting satellites and from the relatively high confidence level in rainfall estimates provided by MW sensors onboard low earth orbiting satellites (Pierre et al., 2011). Therefore satellite-based precipitation products are being used increasingly to monitor drought and potential impacts on hydrology and agriculture in West Africa. For example, the famine early warning systems network (FEWSNET; http://www.fews.net) uses satellite rainfall estimates to provide timely information on emerging and evolving food security issues. Thornton et al. (1997) also showed the potential of crop simulation modelling coupled with satellite

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rainfall estimates (SRFE, see table of acronyms Appendix A) to provide timely estimates of regional production of the major food crops in countries of sub-Saharan Africa.

However, as for any estimate, satellite-based rainfall products systematically suffer from errors and uncertainties that originate from various sources like sensor calibration, algorithmic approximations or sampling (Grimes, 2008; Roca et al., 2010). Since impact, and especially crop yields impact, assessments and forecasts ultimately rely on the accuracy of the input climate data (Berg et al., 2010; Oettli et al., 2011), it is crucial to quantify how the errors in satellite rainfall estimates propagate in impact models. It requires that we go beyond an evaluation of the quality of satellite products (Negri et al., 1995; Laurent et al., 1998; Nicholson et al., 2003; Ali et al., 2005; Dai et al., 2007; Lamptey, 2008; Sapiano and Arkin, 2009; Roca et al., 2010; Jobard et al., 2011) and that we focus on criteria relevant to impact modelling. Such an effort has already been done over the West African region for vegetation (Pierre et al., 2011) and hydrological applications (Gosset et al., 2013). These studies showed that consequences of errors in SRFE on results from impact model outputs are far from linear. Not only is the yearly total precipitation important but also the distribution of rainfall (in time and by intensity classes). The number of rainy days has been shown to be critical for realistic simulations. For instance, Gosset et al. (2013) showed that the runoff computed by a hydrological model in Niger can be overestimated by a factor of 2–3 when using rainfall satellite retrievals with an unrealistic proportion of high rainfall days. Crop models are among the impact models which outputs rely on the accuracy of meteorological input data and in particular on rainfall which is one of the main drivers of yield year-to-year variability in West Africa. For instance Oettli et al. (2011) showed that, when using the SARRAH model for simulating sorghum yield in Senegal with data from regional climate models outputs, major biases in crop yield prediction came first from biases in estimating rainfall and to a less extend from biases in estimating solar radiation. Salack et al. (2012) and Berg et al. (2010) used two different crop models, i.e. respectively SARRAH and ORCHIDEE-Mil, and both agreed on the sensitivity of the simulated crop yield of millet, first to annual rainfall and, secondary to the daily rain frequency. In Nigeria, using the EPIC crop model, Adejuwon (2005) showed that yields of 90-day maize is significantly linked to the rain of the two first months of its cycle, then to the entire growing period rain whereas it is not significantly sensitive to the number of rainy days. Considering such sensitivity to rainfall in crop modelling, the aim of this study is to illustrate how biases in rainfall retrievals propagate into crop yield simulations.

Despite the importance of food security in the region, there are very few papers on the errors generated by the use of rainfall satellite retrievals on crop growth simulations. Using the GLAM crop model (Challinor et al., 2004), Teo (2006) found small differences between simulations of groundnut yields driven by gauge-rainfall and by TAMSAT1 rainfall estimates. However, this study only considered one SRFE which captures reasonably well the rainfall distribution and amounts, and one crop in Gambia.

In the present paper we significantly extend this research by using a set of seven state-of-the-art satellite precipitation products (SPP) to analyse the impact of errors in satellite rainfall retrievals on the performance of crop yield simulation of various cultivars in West Africa. The seven satellite products used in this study represent the diversity of satellite rainfall estimation methods; ranging from real-time products with high errors to products calibrated using rain gauges that provide better quality data but with delays varying from days up to months. We focus on two locations in West Africa; the Sahelian region near Niamey, Niger, dominated by millet cultivation and a wetter region in Djougou, Benin, where our target crop is rain-fed maize.

2. Materials and methods

2.1. Location and ground based rainfall

This study focused on two contrasted areas in West Africa of about 121,000 km^2 each (Fig. 1a).

The Niger area, typical of Central Sahel conditions, is centred on 13.5° N–2.5° E. There, the rainy season lasts approximately three to four months from June to September (Fig. 1b) and the annual rainfall amount is about 450–600 mm. Soils are mainly sandy and infertile. In this area, agriculture is rain-fed, dominated by pearl millet fields and characterized by low input and low yield.

In the Sudanian zone, the Benin site is centred on 9.5° N–2° E. It has a longer rainy season lasting up to 6 months from May to October (Fig. 1c) with about 1200–1300 mm/year and with more than 70% of the annual cumulative rainfall amount usually falling during the months of June to September. In most cases, the soil is sandy in the top layers and loamy to clayey in the subsoil. Maize-yam based cropping systems in the area are rain-fed and characterized by low input.

For each site, the AMMA-CATCH observing system (African Monsoon Multidisciplinary Analysis - Coupling the Tropical Atmosphere and the Hydrological Cycle; http://www.amma-catch.org) provides up to 56 rain gauge measurements sites for the 2003–2009 period (Fig. 1a).

2.2. Satellite data

Seven state-of-the-art satellite precipitation products (SPP) were used. The algorithms of these products combine several types of measurements, mainly infrared (IR) radiation from radiometers on board geostationary earth orbiting satellites and microwave (MW) radiations from passive or active sensors on low earth orbiting satellites. Infrared radiometers measure cloud top brightness temperature with a good space and time resolution whereas microwave sensors provide information that is more directly related to rainfall but with poorer temporal sampling and spatial resolution (Jobard et al., 2011). Characteristics and algorithms of the different products are summarized in Tables 1 and 2. They fall into two categories.

2.2.1. Satellite data only products

Four of the selected SPP use only satellite data to estimate rainfall.

Three of them are near real-time products available within a few days or even a few hours after observation time. The rapidity of data delivery might be offset by lower accuracy relative to in situ observations. The three near-real-time products used for intercomparison in this study are (1) the precipitation estimation from remotely sensed information using artificial neural networks (PERSIANN), which was developed at the Center of Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine; (2) the Climate Prediction Center (CPC) MORPHing (CMORPH) product that has been developed by the NOAA CPC; and (3) the 3B42RT precipitation dataset which is one of the tropical rainfall measuring mission (TRMM), a joint mission between the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), operational data products.

The global satellite mapping of precipitation (GSMAP) project was conducted under a program of the Japan Science and Technology Agency (JST), the product GSMAP-MVK+ is used in this study.

2.2.2. Calibrated rainfall estimates

Three of the evaluated products incorporate raingauge measurements from the global telecommunication system (GTS) network in order to reduce the monthly bias compared to gauges. The global