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Validation of satellite-based rainfall in Kalahari

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ABSTRACT

Water resources management in arid and semi-arid areas is hampered by insufficient rainfall data, typically obtained from sparsely distributed rain gauges. Satellite-based rainfall estimates (SREs) are alternative sources of such data in these areas. In this study, daily rainfall estimates from FEWS-RFE ~ 11 km, TRMM-3B42 ~ 27 km, CMOPRH ~ 27 km and CMORPH ~ 8 km were evaluated against nine, daily rain gauge records in Central Kalahari Basin (CKB), over a five-year period, 01/01/2001-31/12/2005. The aims were to evaluate the daily rainfall detection capabilities of the four SRE algorithms, analyze the spatio-temporal variability of rainfall in the CKB and perform bias-correction of the four SREs. Evaluation methods included scatter plot analysis, descriptive statistics, categorical statistics and bias decomposition. The spatio-temporal variability of rainfall, was assessed using the SREs' mean annual rainfall, standard deviation, coefficient of variation and spatial correlation functions. Bias correction of the four SREs was conducted using a Time-Varying Space-Fixed bias-correction scheme. The results underlined the importance of validating daily SREs, as they had different rainfall detection capabilities in the CKB. The FEWS-RFE ~ 11 km performed best, providing better results of descriptive and categorical statistics than the other three SREs, although bias decomposition showed that all SREs underestimated rainfall. The analysis showed that the most reliable SREs performance analysis indicator were the frequency of "*miss*" rainfall events and the "*miss-bias*", as they directly indicated SREs' sensitivity and bias of rainfall detection, respectively. The Time Varying and Space Fixed (TVSF) bias-correction scheme, improved some error measures but resulted in the reduction of the spatial correlation distance, thus increased, already high, spatial rainfall variability of all the four SREs. This study highlighted SREs as valuable source of daily rainfall data providing good spatio-temporal data coverage especially suitable for areas with limited rain gauges, such as the CKB, but also emphasized SREs' drawbacks, creating avenue for follow up research.

1. Introduction

Rainfall data with good temporal and spatial coverage is important not only to weather forecasters and climate scientists, but also to a wide range of decision makers including hydrologists, as it is the main input in hydrological models. However, in semi-arid to arid areas, particularly in developing countries, such data is lacking due to limited spatial coverage of rain gauges (Kenabatho et al., 2017). The alternative source of such rainfall data is remotely-sensed satellite-based rainfall estimates (SREs), which have the advantage of providing large spatial and temporal rainfall data coverage. These SREs include among others, Famine Early Warning Systems Network Rain Fall Estimation (FEWS-Net RFE) (Herman et al., 1997), Tropical Rainfall Measuring Mission (TRMM) sensor package (Kummerow et al., 1998), Climate Prediction Center (CPC) Morphing Technique (CMORPH) (Joyce et al., 2004) and Precipitation Estimates from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) (Sorooshian et al., 2000).

SREs have been investigated worldwide with various objectives. Some studies investigated rainfall detection capabilities of SREs to define the best performing one, either to be used as independent data source, or to complement limited rain gauge data as input in hydrological models (Arias-Hidalgo et al., 2013; Bauer et al., 2006; Milzow et al., 2009, 2011), or to assess the rainfall spatial and temporal variability (Ringard et al., 2015; Zhang et al., 2017). However, SREs are known to exhibit inaccuracies in the form of systematic (bias) and random errors, which need to be investigated and corrected, where possible, before being used in hydrologic models (Habib et al., 2014; Nicholson et al., 2003). These errors might be due to different factors, among them being SREs algorithm estimation through cloud top reflectance, thermal radiance estimation, infrequent satellite over-passes, orbital drifts, topography and precipitation retrievals (AghaKouchak et al., 2009; Dinku et al., 2008; Joyce et al., 2004; Kummerow et al.,

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2004). Large SREs' biases are frequently reported, also over the African continent (Nicholson et al., 2003). These biases are particularly distinct when comparing daily SRE with daily rain gauge data (Artan et al., 2007), but decline when analyzing monthly or longer timescales because of temporal data accumulation (Dembele and Zwart, 2016).

SREs can be corrected for systematic errors; appropriate methods are well documented in literature. For example, Habib et al. (2014) investigated the effect of bias correction of SREs on runoff simulation at the source of the Upper Blue Nile applying three multiplicative bias correction schemes: Time and Space Variable, Time Variable and Space Fixed and Time and Space Fixed. They used these three bias correction schemes to analyze the spatio-temporal variability of CMORPH bias and to identify critical aspects of such variability from a hydrologic perspective.

Validation of various SREs using rain gauge data have been conducted worldwide. However, little of such work has been done in Africa due to limited spatial coverage of rain gauges. Few examples include study by Adeyewa and Nakamura (2003), who used systematic and random error statistics to validate TRMM radar rainfall algorithm over main climatic regions in Africa at monthly and seasonal time scales. Their results showed that the random and systematic errors were sensitive to the seasonal rainfall difference and spatial location. Dinku et al. (2010) used descriptive and categorical statistical validation methods to evaluate the performance of CMORPH ~ 27 km, TRMM-3B42 and TRMM-3B42RT in rainfall detection over mountainous regions of Ethiopia (also Colombia) at daily time scale. In that study, CMORPH ~ 27 km performed better than TRMM-3B42 and TRMM-3B42RT, even though performances of all the SREs were low. Romilly and Gebremichael (2011) evaluated the accuracy of CMORPH, PERSIANN, TRMM-TMPA and TRMM-3B42RT over six river basins in Ethiopia through bias ratio, spatial pattern and dependence of bias ratio of SREs on elevation at monthly and seasonal time scales. Results of that study showed that CMORPH, TRMM-TMPA and TRMM-3B42RT outperformed PERSIANN. Haile et al. (2013) investigated the accuracy of 1-hourly, 8 km spatial resolution CMORPH algorithm over Gilgel Abbay Basin, also in Ethiopia. Their results showed a significant rainfall variation across the basin, although that variability was poorly correlated to gauge observations, not only in spatial but also in temporal manner. Their validation methodology included descriptive and categorical statistical verification.

Few SREs related studies have been carried out in Southern Africa where this study took place. They include a study by Liechti et al. (2012), who compared and evaluated TRMM-3B42 v6, FEWS-NET RFE 2.0 and CMORPH 0.25^0 against daily, decadal and monthly rain gauge data, to choose one that could be used as input for hydrological model of the Zambezi Basin. In that study, FEWS-Net RFE 2.0 and TRMM-3B42 had better comparative performances than CMORPH. Despite better performance of FEWS-NET RFE 2.0, the TRMM-3B42 with a daily time step was finally chosen because of its longest data record. Tote et al. (2015) evaluated the performance of TAMSAT African Rainfall Climatology and Time-series (TARCAT 2.0), FEWS-NET RFE 2.0, and Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) by comparing their decadal estimates with ten days rain gauge data for drought and flood monitoring in Mozambique using categorical statistics. In that study, FEWS-Net RFE 2.0 and CHIRPS performed better than TARCAT 2.0 because they both have been inherently bias corrected using the Global Telecommunication Station (GTS) rain gauge data network. Finally, in the south-eastern Botswana, Kenabatho et al. (2017) evaluated the daily performance of TRMM and spatial rainfall from the Generalized Linear Models (GLMs) (Chandler and Wheater, 2002) on rainfall detection in the Notwane catchment area using quantitative (descriptive) and categorical statistics. Their results indicated the potential of SREs in augmenting the limited rain gauged data in semi-arid areas.

This study was motivated by the lack of systematic evaluation of different SRE rainfall detection performances in the Kalahari area to date. The Kalahari area has sparse rainfall monitoring network but large demand for valuable spatio-temporal rainfall data by governmental and non-governmental offices of the Kalahari countries, i.e. Botswana, Namibia and South Africa. Such data can be provided by SREs, however in different parts of the world different SREs perform optimally, so the need for this study.

The objectives of this study were then formulated as following: 1) to evaluate daily rainfall detection capabilities in the CKB for the four SREs: i) FEWS-NET RFE 2.0 with ~ 11 km spatial resolution; ii) TRMM-3B42 v7 with ~ 27 km spatial resolution; iii) CMORPH v1 with 8 km spatial resolution; and iv) CMORPH v1with ~ 27 km spatial resolution.; 2) to analyze and present spatio-temporal variability of rainfall in the CKB; 3) to perform bias correction to the four SREs and evaluate if the bias correction scheme adequately addressed the SREs' systematic errors.

2. Study area and datasets

2.1. Study area

The Central Kalahari Basin occupies the central part of Botswana (~ 181,000 km^2) and small western part (~ 14,000 km^2) of Namibia (Fig. 1). It extends from 20.50° S to 24.90° S and from 18.70° E to 26.75° E. It is one, large-scale hydrogeological basin, which is a catchment of the fossil Okwa-Mmone river system (de Vries, 1984). Majority of the CKB is pretty flat, having a topographic gradient of < 0.001 (Fig. 1) and ~ 90% area occupied by Kalahari Desert (Batisani and Yarnal, 2010).

The CKB climate is semi-arid to arid because of its average position under the descending limb of the Hadley cell circulation (Batisani and Yarnal, 2010). Most of the CKB rainfall is from convection processes such as instability showers to thunderstorms, which are several orders of magnitude smaller than the synoptic systems (like the Inter-Tropical Convergence Zone) controlling the supplied moisture of air-masses. The incidence of rainfall in the region is highly spatially and temporally variable (Obakeng et al., 2007), with highly localized rainfall showers (Bhalotra, 1987). Almost all the rainfall occurs during the summer months of September to April, with an annual average ranging from 380 mm in the southwestern, to 530 mm in the northeastern parts of the study area.

2.2. Datasets

This study was carried out using five-year daily data, from 01/01/2001 to 31/12/2005.

2.2.1. Meteorological data

Daily rainfall data of twelve rain gauge stations for the five-year study period were sourced from the Botswana Department of Meteorological Services (DMS). After screening, only nine stations were left to be used in this study (Table 1).

The three stations removed exhibited many data gaps. The remaining nine stations were also affected by data gaps (Table 1), although the percentage of missing data was considered low. This data was used as a reference for the assessment of the SREs, neglecting days when stations had data gaps.

2.2.2. Satellite data

Time series of four daily SREs for the five-year study period were downloaded online; their properties and sources are summarized in Table 2. All the SREs' grids attributed to each of the nine rain gauge locations are scale-projected in Fig. 2 – note that TRMM and $CMORPH_{27}$ grids coincide.

The RFE is a blended product, based on cold cloud duration (CCD) derived from: METEOSAT thermal infrared (TIR), Special Sensor Microwave/Imager (SSM/I), Advanced Microwave Sounding Unit (AMSU) (Herman et al., 1997). The RFE data is inherently bias-

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