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Research papers

Using long-term daily satellite based rainfall data (1983–2015) to analyze spatio-temporal changes in the sahelian rainfall regime

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ABSTRACT

The sahelian rainfall regime is characterized by a strong spatial as well as intra- and inter-annual variability. The satellite based African Rainfall Climatology Version 2 (ARC2) daily gridded rainfall estimates with a 0.1° × 0.1° spatial resolution provides the possibility for in-depth studies of seasonal changes over a 33-year period (1983–2015). Here we analyze rainfall regime variables that require daily observations: onset, cessation, and length of the wet season; seasonal rainfall amount; number of rainy days; intensity and frequency of rainfall events; number, length, and cumulative duration of dry spells. Rain gauge stations and MSWEP (Multi-Source Weighted-Ensemble Precipitation) data were used to evaluate the agreement of rainfall variables in both space and time, and trends were analyzed. Overall, ARC2 rainfall variables reliably show the spatio-temporal dynamics of seasonal rainfall over 33 years when compared to gauge and MSWEP data. However, a higher frequency of low rainfall events (<10 mm day^{-1}) is found for satellite estimates as compared to gauge data, which also causes disagreements between satellite and gauge based variables due to sensitivity to the number of days with observations (frequency, intensity, and dry spell characteristics). Most rainfall variables (both ARC2 and gauge data) show negative anomalies (except for onset of rainy season) from 1983 until the end of the 1990s, from which anomalies become mostly positive and inter-annual variability is higher. ARC2 data show a strong increase in seasonal rainfall, wet season length (caused by both earlier onset and a late end), number of rainy days, and high rainfall events (>20 mm day^{-1}) for the western/central Sahel over the period of analysis, whereas the opposite trend characterizes the eastern part of the Sahel.

1. Introduction

The Sahel is known as one of the largest semi-arid regions in the world and livelihoods of the sahelian rural population depend primarily on rain-fed agriculture and livestock farming (Leisinger and Schmitt, 1995). The Sahel zone is characterized by high intra-annual variability, affecting water resources and food security (Le Barbé et al., 2002; Nicholson, 1993, 1989; Nicholson and Palao, 1993). The region has experienced several decades of abnormally dry conditions over the past 50 years, including two sequences of extremely dry years in 1972–1974 and 1983–1985 (Hulme, 1992; Le Barbé and Lebel, 1997). These periods, well known as the Sahel droughts, caused severe famines, human and livestock deaths, land abandonment, and large-scale migrations. Sahelian sedentary farmers and pastoralists are consequently forced to adapt to the general decrease in water resources and increase in rainfall variability (Mortimore and Adams, 2001; Romankiewicz et al., 2016). Water availability and timing of precipitation events are key factors for the agricultural crop production (Berg et al., 2009; Sultan et al., 2005) and primary productivity of herbaceous and woody vegetation in the Sahel (Huber et al., 2011). The timing of start of the wet season is pivotal, as most farmers and pastoralists form decisions on cropping and livestock movements on the basis of the occurrence of the first rains (Ingram et al., 2002). Finally, the timing of the seasonal rainfall is decisive; e.g., late season rainfall may lead to high annual/seasonal rainfall sums, however being of little use for crops and herbaceous vegetation, which are both photoperiodic (Breman and Kessler, 2012). Any changes in the overall rainfall regime will have profound impacts on livelihoods. However, the network of rain gauge stations in Africa, and particularly in the Sahel, has decreased significantly in recent years (Eklund et al., 2016; Sanogo et al., 2015), adding considerable uncertainty to datasets based on station data only

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(e.g., the CRU (Climate Research Unit) rainfall datasets) and analyzes hereof (Eklund et al., 2016), hampering studies of rainfall regime changes. Moreover, the Sahel rainfall spatial heterogeneity is not well captured by the gridded CRU datasets (0.5° spatial resolution) or by widely dispersed station data from gauge observations. Seasonal rainfall is found to vary significantly at scales of a few tens of km (meso-scale) (Nicholson, 2000) and spatial variability at the daily timescales is also high due to the predominantly convective nature of precipitation during the rainy season (Lebel et al., 2003; Laurent et al., 1998a,b).

Precipitation estimates from satellites provide repetitive, timely, objective, and cost-effective information on the spatio-temporal distribution of rainfall. Estimates of with a high spatio-temporal resolution have been available for the African continent since the 1980s from the METEOSAT satellites and provide vital information on rainfall in areas with an insufficient station network (Maidment et al., 2015). A variety of rainfall datasets have been produced using convective cloud top temperature and by applying the cold cloud duration (CCD) technique (Adler et al., 1994). The performance varies considerably, and calibration and evaluations using rain gauges of such CCD based satellite rainfall products are critical (Jobard et al., 2011; Laurent et al., 1998a,b; Love et al., 2004; Nicholson et al., 2003a,b). An acceptable agreement is often found between satellite and gauge data, even though inter-annual variations in bias are commonly found (McCollum et al., 2000; Nicholson et al., 2003a,b). Yet, the satellite data used in these studies mostly covers relatively short periods of time and only decadal or monthly rainfall observations are evaluated (Moron, 1994; Nicholson and Palao, 1993; Sanogo et al., 2015; Maidment et al., 2015). Only two recent studies have analyzed the satellite/gauge relationship on a daily scale over Sahel (Dembélé and Zwart, 2016; Sanogo et al., 2015), both reporting a weak agreement (r^2 below 0.3) between satellite and gauge data.

Advances have been made in understanding the regional circulations and their relationships to water vapour transport in the West African region (Thorncroft et al., 2011). However, most studies of changes in the sahelian rainfall define the rainy season as a fixed set of months (from either gauge or satellite data) (Jobard et al., 2011; Nicholson, 2005; Nicholson et al., 2003a,b; Sealy et al., 2003). The four months from June to September are usually considered as the rainy season since more than 80% of the annual rainfall falls during this period (Lebel et al., 2003; Sanogo et al., 2015). Only a few scholars have studied changes in the Sahel rainfall regime based on variables such as onset and cessation of the rainy season, rainy days, rainfall intensity from gauge/satellite data (Nicholson and Palao, 1993; Sanogo et al., 2015; Dunning et al., 2016) that can only be resolved using daily rainfall data.

In this study we evaluate the use of the satellite based Africa rainfall climatology version 2 (ARC2) dataset (Novella and Thiaw, 2012) (available from 1983 to the present at daily time steps with a $0.1° \times 0.1°$ spatial resolution) in the characterization of the Sahel rainfall regime and changes herein. The high temporal and spatial resolution enables a comprehensive study of spatially distributed rainfall variables describing the rainfall regime (onset and cessation dates, length of the wet season, seasonal rainfall amount, rainy day, intensity and frequency of rainfall events, dry spell characteristics (number, intensity, and cumulative days of dry spells)). All variables are validated against rain gauge data over a 33-year period. The robustness of the ARC2 rainfall metrics and furthermore intercompared with the global coverage MSWEP dataset (Beck et al., 2017) produced also with a daily temporal resolution. The objectives of this study are threefold: (1) to evaluate the agreement between rainfall variables derived from ARC2, MSWEP and available long-term continuous rain gauge data of daily resolution; (2) to analyze selected ARC2 and gauge derived variables over the full time period; (3) to study the spatial variability in temporal trends of ARC2 derived variables.

2. Materials and methods

2.1. Study area

The Sahel extends from the Atlantic Ocean in the west to the Red Sea in the east and constitutes a transition zone between the arid northern and the humid southern eco-regions (Fig. 1). The delineation was derived from the ARC2 average annual rainfall (1983–2015) with northern/southern boundaries of 100 mm and 700 mm, respectively (Lebel et al., 2009). Typically, the rainy season lasts from June to early October with a peak in August (Le Barbé and Lebel, 1997) and is characterized by a high inter-annual variability, with a coefficient of variation of the mean annual rainfall ranging from 15% to 30% (Sivakumar, 1989). The climate is directly linked to the West African Monsoon with a decreasing rate of annual rainfall of approximately 1 mm km^{-1} along a south-north gradient (Lebel et al., 1997; Frappart et al., 2009). The comparison between ARC2 rainfall and gauge measurements focuses on western and central parts of the Sahel, where the availability of gauge measurements without substantial data gaps is more abundant as compared to the eastern Sahel.

2.2. Datasets

2.2.1. ARC2 dataset

The ARC2 (African Rainfall Climatology Version 2) satellite based daily rainfall dataset is available from 1983 – present at a $0.1° \times 0.1°$ spatial resolution (approximately 11×11 km). ARC2 builds on ARC1 that is developed using the algorithm applied in the RFE2 (Rainfall Estimation version 2) which is found to be amongst the most reliable products of satellite based datasets covering Africa (Love et al., 2004). The difference as compared to RFE2 is that ARC1 uses only gauge and infra-red data whereas RFE2 uses additional microwave data, which is not available prior to 1995 (Love et al., 2004). Ultimately, ARC2 is a revision of ARC1 with a recalibration of the 1983–2005 period (Novella and Thiaw, 2012).

2.2.2. MSWEP dataset

The global coverage MSWEP (Multi-Source Weighted-Ensemble Precipitation, version 1.2) rainfall dataset is provided with 3-h temporal resolution for the period 1979–2015 in a 0.25° spatial resolution (Beck et al., 2017). MSWEP is developed by merging the highest quality precipitation data sources available as a function of timescale and location from the combined use of rain-gauge measurements, satellite observations, and estimates from atmospheric models (Beck et al., 2017).

2.2.3. Rain gauge dataset

The gauge rainfall is derived from the Global Historical Climatology Network (GHCN-Daily) (Menne et al., 2012). GHCN rainfall measurements from rain gauge stations are considered to be the most accurate and reliable source of precipitation data in the region (Durre et al., 2010). Stations with at least 80% data availability throughout the entire period 1983–2015 were selected as references for the comparison to ARC2 data, leading to the selection of 30 stations distributed from 17°W to 15°E (Fig. 1). No gap-filling of missing daily observations was done. When a record is missing at a given station, the corresponding ARC2 record is discarded to provide the most accurate comparison of datasets.