Evaluation of Two Global Rainfall Models for Water Resources Planning and Management in Nigeria

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Abstract- Given the sparseness of weather stations in Nigeria, there is an increasing need for alternative sources of rainfall data such as satellite measurements, numerical models, and reanalysis. Nevertheless, the complexity of such data requires proper evaluation and validation. Therefore, this study evaluated two globally available rainfall products from Climate Research Unit (CRU) and University of Delaware (UNIDEL) using rain gauge data obtained from Nigerian Meteorological Agency (NIMET), over a period of twenty years (1980-1999) covering 24 stations. Time series plot and statistical tools were used to evaluate the products on annual, seasonal and zonal basis. The results show that the two products demonstrated comparable ability and sufficiently captured the spatial and temporal patterns of rainfall over the country. However, the products overestimated and underestimated during the dry and rainy seasons, respectively. Although, correlation was comparatively high between 0.3 and 0.8, but negative in few instances, mean bias error (MBE) and root mean square error (RMSE) were generally high depicting high random error. The performance of the products was best in the Sahel, followed by the Savannah and Forest zones, with UNIDEL showing better performance in most cases. Consequently, we recommend further studies to validate the present results on the use of gridded data in the country.

Keywords- evaluation, CRU, UNIDEL, rain gauge, rainfall products.

1 INTRODUCTION

Adequate knowledge of the vagaries of climate variables is important in climate research and agricultural water resources management given the present challenges of climate change that currently faces the world. While many water resources structures are constructed with the assumption of stationarity in climatic variables, recent events may have invalidated such an assumption, thus presenting fresh challenges to climatologists and water resources planners. However, amongst the variables of climate, rainfall is generally accepted as the most important all over Africa (Diro et al., 2009), especially given the reliance of the economy of most of the countries in the region on rain-fed agriculture (Diro et al., 2009; Maidment et al., 2012). Naidu et al. (1999) stated that rainfall is an important meteorological parameter which has direct application to agricultural production and other aspects such as water resources. For instance, in the area of modelling, knowledge of local hydrological conditions in form of rainfall time series data is required (Kovář et al., 2015). Consequently, accurate estimates of precipitation on varying space and time scales becomes important not just to the weather forecaster or climate scientists, but also to a wide range of decision makers dealing with sectors such as water resources and agriculture (Nair et al., 2009).

Rain gauges are sparsely distributed across many parts of Africa and in Nigeria, culminating in dearth of rainfall data both in quantity and quality. Diro et al. (2009) noted that due to sparseness of observations, available gauge network cannot provide adequate and timely information about the rainfall pattern in many parts of Africa. Although gauge measurement is still the conventional method of rainfall data collection, capable of providing longer observations (Yatagai et al., 2009), it lacks capacity to provide reliable spatial representation of precipitation (Gruber and Levizzani, 2008).

Meanwhile, Abiola et al. (2013) stated that records of precipitation are significantly insufficient in Nigeria as a result of sparseness of rain gauges network being used for data collection in the country. Further to this, available evidence is to the effect that some synoptic weather stations are currently non-operational in the country owing to paucity of funds and perhaps poor maintenance. In some instances, long rainfall records contain missing data as a result of the manual methods of recording that can be very subjective. Thus, available data in the country may be grossly inadequate in terms of spatial and temporal coverage for extensive studies in agro-meteorology and water resources management.

Consequently, alternative approaches to rainfall measurement have been developed to include the use of satellite algorithms, reanalysis and numerical models. However, many of the data sources are prone to errors that discourage their direct usage without initial evaluation. For instance, satellite rainfall data are prone to errors from sources such as temporal sampling, instrumentation and algorithm (Gebremichia et al., 2005; Hossain and Huffman, 2008), which makes assessments of their accuracy a pre-requisite task (Romilly and Gebremichael, 2011). In this regard, validation and evaluation of satellite rainfall products have been carried out by various scientists over many regions of Africa and beyond (e.g. Adeyewa and Nakamura, 2003; Chiu et al., 2006; Askary et al., 2007; Nair et al., 2009). In the same vein, similar studies have been undertaken on reanalysis and numerical models (e.g. Dinku et al., 2008; Diro et al., 2009; Maidment et al., 2012), but information are scarce with respect to similar study over Nigeria. However, the complex physics behind the development of the products and the operational algorithms involved call for adequate evaluation and validation over the various regions of the world. Therefore, the objective of the present study is to evaluate two globally available rainfall products from Climate Research Unit (CRU) and University of Delaware (UNIDEL) over Nigeria.

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2 MATERIALS AND METHOD
2.1 THE STUDY AREA
The study area, Nigeria, is located on the latitude 4° to 14° N of the equator and longitude 3° to 15° E of the Greenwich Meridian (approximately). Given the massive geographical coverage of about 923,200 km² and the great extent from south to the north (1100 km), the climate of the country appears to be more diverse than those of other countries in West Africa. The climate is semi-arid in the north, humid in the south and humid strip along the coast with an average rainfall of about 2000 mm. The ecological zones of the country can be broadly grouped into three- Forest, Savanna and the Sahel zones (Fig. 1). Two distinct seasons are recognized in Nigeria based on the frequency of rainfall: a wet season from April to October and a dry season which usually begins in November and ends in March. As a result of the tropical maritime (TM) air mass which usually enters into the country through the southern zone, rainfall mostly commences in the south around February on a scattered note, becomes stable in April and ascends to the northern parts where it actually starts about May or June (Ojo, 1977). The height of the rainy season in the south is July after which a short dry spell occurs in August (August break), matching with the peak of the season in the northern part. A period also locally known as Harmattan occasionally occurs around November of the year, when moist air from the tropical maritime (TM) meets with hot, dry and often dust-laden tropical continental (CT) air mass.

2.2 DATASETS
The study utilized rain gauge data obtained from the data section of the Nigerian Meteorological Agency (NIMET), Oshodi Lagos, Nigeria. The Agency is affiliated to World Meteorological Organization (WMO), a specialized agency of the United Nations. The daily rainfall data used in this study covered the period between 1980 and 1999 over 24 stations. Also, global rainfall products were obtained from Climate Research Unit (CRU) and University of Delaware (UNIDEL) covering the same period. All the data were aggregated to annual time series for analytical convenience and to conserve space. The physics of the two products used is beyond the scope of this work, however, interested readers are referred to the authors and web addresses provided in Table 1.

Table 1. Brief description of the two rainfall products

| Model/Product | Acronym | Spatial Resolution | Reference/web page |
|---------------|---------|-------------------|-------------------|
| Climate Research Unit | CRU | 0.5° x 0.5° | Willmott and Matsuura (2001), Legates and \cite{2001} |
| University of Delaware Precipitation | UNIDEL | 0.5° x 0.5° | http://climate.geog.udel.edu/~climate/html |

2.3 DATA ANALYSIS
Evaluation of data was carried out on annual, seasonal and zonal basis. Time series plot of data was done to determine the performance of the products on the annual basis over the period of 20 years for all stations. Four seasons- December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON) were identified according to Adeyewa and Nakamura (2003) upon which data were averaged and compared, for the seasonal analysis. For the zonal evaluation, Nigeria was broadly classified into three ecological zones (Figure 1) as follows:

(a) Forest - 4.5° - 7.5° N and 2.5° – 12° E
(b) Savanna - 7.5° – 11° N and 3.5° - 13.5° E
(c) Sahel - 11° -14° N and 3.5° – 14° E

Three statistical indicators; mean bias error (MBE), root mean square error (RMSE) and correlation coefficients (µ) were used to compare the performance of the products over the climatic zones. All computations were based on standard mathematical formulae available in all relevant statistics textbooks.

3 RESULTS AND DISCUSSION
3.1 EVALUATION ON ANNUAL BASIS
The annual time series plot of the two products and the rain gauge data (one station in each geo-political zone shown to save space) are shown in Fig. 2. The results show that the two rainfall products (CRU and UNIDEL) displayed particularly good agreement with the rain gauge data, except in few stations and years where there were under-estimation and over-estimation at different degrees. For example, in Bida, Nguru, Kaduna, Sokoto (not shown), Yelwa and Ilorin, the products adequately mimicked the pattern of the observed data very well in quantity and quality; the temporal patterns are very similar with the ground truth in all the years under study.

Under-estimation and over-estimation subject to the station are generally less than 500 mm/yr and barely noticeable in the stations mentioned, except during the late 1990s. However, in Lokoja, Makurdi, Akure, Calabar (not shown) and Ikeja, where under-estimation and over-estimation are evidently high, the patterns were still similar to gauge data. Aside from Makurdi and Kano (not shown), Akure and Enugu where both CRU and UNIDEL displayed very conspicuous under-estimation of different magnitudes especially between 1980 and 1990, the products over-estimated rainfall in most of the years in other stations in this group. In Maiduguri, Gusau, Kano and Makurdi (not shown), a predominantly interesting...
and different scenario was detected. While the products show very glaring under-estimation between 1980 and 1995, they seemed to have agreed better near the end of the last century in both Maiduguri and Gusau; the contrary was however the case in Kano and Makurdi.

Overall, the two products agree very well with the rain gauge data in many more stations especially during the period 1980-1990 than close to the end of the last century. The end of the last century may have experienced several high intensity rainfall and cloud cover in Africa which the models might not have effectively and adequately captured as compared with the situation in the early 1980s after the recovery from the drought of the 1960s. There seems to be a general agreement as to the assumption that the decade 1980 has been the driest recently (Nicholson 1993; Fasona and Omojola, 2005). Therefore, the present result can be attributed to the apparent incorporation of very few moisture-related observations in the algorithms (Tolika et al., 2006). Moreover, inability of many of the rainfall estimation algorithms to distinguish between precipitating and non-precipitating clouds has been observed as a major problem (Karaseva et al., 2012). Hence, the products may not have adequately recorded cloud covers and convective rainfalls which were very rampant during the period. Despite this, inter-annual variability was higher than intra-annual.

Fig. 2: Time series plot to compare rain gauge data with the two products showing one station in each of the six geo-political zones of Nigeria

3.2 EVALUATION ON SEASONAL BASIS

First, it is evident that the seasonal average for the two products presented the same pattern over the period under study (Fig. 3). In the same vein, there is no doubt that the products were in very good agreement with gauge data in June-July-August (JJA) generally taken as the peak of the rainy season in Nigeria. Nonetheless, CRU seemed to have agreed more with the gauge than UNIDEL during this season and the pattern was almost similar in other seasons and in many more stations. While the performance of the products could not be easily judged in some stations during the December-January-February (DJF) season, there are reasons to believe that the products also adequately captured rainfall, but with less precision during this period as shown in the few stations where their performances are observable. The reason for this is not clear, however, it may not be unconnected with the inability of many of the sensors and algorithms used by the rainfall products to effectively capture light rainfall. Dinku et al. (2008) and Javanmard et al. (2010) had observed the limited ability of satellite products to depict precipitation for dry seasons while commending their ability to do same during the wet seasons. In stations where wide discrepancies were noticed, the two products underestimated rainfall, specifically during the transition period to rainy season (spring), March-April-May (MAM). On the contrary, during transition to the dry season (autumn), September-October-November (SON), it appears as if both products also overestimated rainfall as compared with the gauge. Kid (2004) had posited that ability to compensate for inability to identify light rainfall when recording rainfall of high intensity can add to the reliability of a rainfall algorithm.

In general, the results show that the two products possess similar ability to detect rainfall in all the seasons. It could be reasoned that the overestimation observed during SON (transition to dry season) might have been a form of compensation for the underestimation seen during the same transition to the rainy season. On the overall, the products look to be more dependable during the peak of the rainy season (summer), i.e. JJA than during the remaining seasons of the year.

Fig. 3: Seasonal comparison of the two products with rain gauge showing one station in each of the six geo-political zone
3.3 Evaluation on Zonal Basis

The results of statistical analysis used for zonal evaluation are shown in Fig. 4. For the products to be accurate, the general assumption is that MBE should be close to zero, correlation coefficient ≥ 0.5 and RMSE should be very small. CRU shows decreasing overestimation moving north from about 500 mm/yr in Calabar (humid-forest belt) to about 100 mm/yr in Benin (rain-forest) after which underestimation commenced in Akure (-150 mm/yr) and continued to the Savannah zone at increasing magnitude (-300 mm/yr) as shown in Lokoja and Makurdi. However, the increase in underestimation did not endure further in the zone as Jos, Bida and Bauchi depict slight biases that are relatively close to zero. These overestimations and underestimations may not be unconnected with the methods used in generating the rainfall products. For instance, in the case of CRU, transformation of gridded data to country averages was done by allocating each 0.5° grid-box to one country and calculating the weighted mean of the constituent grid-boxes of each country (Mitchell et al., 2002). Therefore, given the large geographical spread of Nigeria, there is high tendency for the masking of local convective rainfall.

On the other hand, the sparseness of weather stations which usually serves as source of raw data for many rainfall archiving organisations and the effects of topography are other contending issues (Mitchell and Jones, 2005; Yen et al., 2020). Except in Maiduguri and Gusau where CRU display minor overestimation (+ve bias), underestimations are generally less than -200 mm/yr in other stations in the Sahel zone. On the contrary, UNIDEL demonstrated underestimation (-ve bias) which reduced from about -400 mm/yr in Calabar to ≤-50 mm/yr in Enugu, Ikeja and Ogoja moving north. Overestimation increased from about 100 mm/yr around Akure (rain-forest belt) reaching its peak (200 mm/yr) around Lokoja after which it reduced in Yola to about 100 mm/yr. Over the Sahel zone, UNIDEL exhibited underestimation of less than -100 mm/yr, apart from Kano; however, there were slight overestimations in both Nguru and katsina. The results of the MBE are generally higher for CRU than in UNIDEL in most stations.

Correlation shows great departure from the results of the MBE as it portrays varied patterns with respect to the zones. For instance, CRU depicts very diverse correlation figures in all the zones which ranged from -0.22 (Minna) in the Savannah to 0.74 (Kaduna) in the same zone giving an average absolute value of 0.44. Similar scenario was observed in the Sahel where the values ranged from -0.27 (Maiduguri) to 0.71 (Sokoto) with an average absolute correlation value of about 0.44. The case in the Forest zone is, however, slightly different as no negative correlation value was recorded. Nevertheless, the values ranged from 0.03 (Benin) to 0.72 (Ikeja), with an average absolute value of about 0.39. Also, similar pattern was exemplified by UNIDEL as its value ranged from -0.22 (Benin) to 0.5 (Owerri), with an average absolute value of 0.34. In Savannah, correlations range from -0.2 (Jos) to 0.84 (Bida), giving an average absolute value of 0.52. Furthermore, in Sahel, correlations range from -0.27 (Maiduguri) to 0.84 (Sokoto) with an average absolute value of 0.51. Although, the average absolute correlation values for the two products are almost the same in Savannah and Sahel, there are negative values in at least two stations in Savannah for UNIDEL. Thus, the two products could be said to have done better in the Sahel than in Savannah and Forest zones. Moreover, correlation is stronger (≥ 0.5) in many more stations in the Sahel for both products, but recorded negative value in one station each. The results indicate that the two products were able to replicate the gauge measurements in the greater number of the stations in all the three zones.

Biases similar to that of MBE are shown by the results of the RMSE. CRU gave a decreasing value of RMSE from about 650 mm/yr in Calabar (humid-forest belt) northward to about 300 mm/yr in Enugu and Owerri (rain-forest belt). In the Savannah, CRU also depicts error values which reduced from about 400 mm/yr in Lokoja to a little above 100 mm/yr in Kaduna, continuing in similar manner upward north in Sokoto, Potiskum and Nguru, but rather increased to above 300 mm/yr around Maiduguri and Kano, all in the Sahel.

However, UNIDEL shows a slight deviation from the performance of CRU as the highest error value decreased from about 450 mm/yr (Calabar) through Benin (about 340 mm/yr) to a little less than 200 mm/yr in both Ogoja and Ikeja, in the Forest zone. Moving further north, the error values in the Savannah zone decreased from slightly above 300 mm/yr (Lokoja) to less than 100 mm/yr in Minna after which it rose to about 160 mm/yr in Ilorin, Bauchi and Yola. In the Sahel, the errors were generally

Fig. 4: Statistical evaluation of the two products on zonal basis; mean bias error (MBE), correlation coefficient (CORREL) and root mean square (RMSE)
low, falling from a little close to 200 mm/yr in Kano to slightly above 50 mm/yr in Gusau after which it rose again to above 100 mm/yr in Potiskum. The RMSE values were generally lower for UNIDEL; less than 200 mm/yr in majority of the stations, while that of CRU were greater, between 100 mm/yr and 400 mm/yr in all the stations. This indicates that UNIDEL was better in overcoming random errors than CRU. The higher susceptibility of CRU to random error might be mainly attributable to the use of elevation in constructing its climatological values (Dinku et al., 2008).

4 CONCLUSION
The capacity of CRU and UNIDEL to accurately capture observed rainfall in Nigeria was assessed. To achieve this, an extensive evaluation of the two products with gauge observations was carried out for a 20-year period, on annual, seasonal and zonal basis. In view of the complexity of the climate and terrain of the country, the present results are found encouraging. The two products depicted very similar performances; however, they were better in the dry years, especially between 1980 and 1990. Additionally, the products were also better able to mimic rain gauge during the summer season (June-July-August) than in the other seasons. The zonal evaluation, nevertheless, show diverse performances of the products with UNIDEL performing better in all the three climatic zones judging from the error statistics. For this reason, it is safe to conclude that UNIDEL is more reliable for use in studies where rainfall data is needed in any geographical location in the country.

It can be further concluded that the two products have the capacity to provide reliable information for studies in the various areas of water resources planning and development such as streamflow modelling, flood frequency analysis, and climate change impacts studies in basins, especially in such stations as Bida, Nguru, Kaduna, Sokoto, Yelwa and Ilorin, given their very impressive performance in those stations. Thus, the results of the study show the need for validation and evaluation of the rainfall products and other similar ones before their application in any geographical setting. However, the use of gridded (interpolated) gauge data to the same spatial resolution with the global products is suggested for further studies. To further validate the consistency of the rainfall products, the model’s outputs could be compared with gauge results when the two are separately used to drive runoff models.

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