VALIDATION OF SATELLITE-BASED RAINFALL MEASUREMENTS IN ARID AND SEMI-ARID REGIONS OF SUDAN

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ABSTRACT

Rainfall is the major input of water in seasonal and perennial water courses and catchments and thus it needs careful consideration in any hydrological model. In arid areas mankind has been dependent on the bare natural resources since the early history. Although rainfall measurement looks as straightforward task, it is practically difficult to accurately evaluate the rainfall at it is of temporal and spatial contexts. To measure the rainfall in a basin it is not practical or possible to catch all the rainfall occurring in an area; and time and space sampling methods are needed, and here comes the source of the errors. Few rain gauges scattered in a basin with daily temporal scale, in the best cases, are not able to catch the temporal and spatial variability of this type of rain nature in arid regions. One of the major problems in arid areas in the locality of the rainfall storms, especially during the summer season which makes any number of gauges not really efficient to detect such storms. Thus, development of areal rainfall evaluation techniques that is able to observe the rainfall in high spatial and temporal resolution represents an important solution for the problem of the rainfall data scarcity in arid regions. In this study the potential of using satellite data in arid areas have been highlighted. Data obtained from TRMM sensors have been examined. Monthly data obtained from combined sensors and ground gauges have been compared to ground measurements. The rainfall data obtained from TRMM multi-satellite data set (combined sensors) have been used in order to validate the potential of satellite data over arid areas. The ground data used for validation were obtained for 15 stations on the arid and semi-arid region of The Republic of The Sudan. The average correlation coefficient was 0.86 ($P<0.01$). The study also showed high variation in the correlation coefficient under different rainfall depths and locations.

1. INTRODUCTION

1.1 Environment of arid regions

The main characteristic of arid regions is lack of rainfall or moisture (Slatyer and Mabbutt, 1964). Generally, aridity is a climatic phenomenon based on the prevailing environmental conditions over a certain region (Agnew and Anderson, 1992). Arid regions can be divided into three categories: extremely or hyper arid, arid, and semi-arid. Some other classifications for the arid areas are based on the atmospheric conditions, crop production, natural vegetation cover, and available moisture for plants. Agnew and Anderson (1992) consider the main difference between the desert, land with low rainfall and sparse vegetation, and arid and semi-arid regions. The geomorphologies of the arid regions are varied from active tectonic mountainous regions to stable areas. The major features of arid areas are alluvial fans, sand dunes, bed rocks, and dry mountains (Agnew and Anderson, 1992).

Although rainfall measurement is simple and a straightforward task, it is practically difficult to accurately evaluate the rainfall at its temporal and spatial contexts. To measure rainfall in a catchment it is not practical or possible to record all the rainfall occurring in an area; and sampling methods over space and time are needed, and here comes the source of the errors. Rainfall is usually measured through a network of rain gauges and expressed as depth of water in mm or inches. In arid and semi-arid regions, the accuracy of sampling of the rain sampling techniques (temporal and spatial) is very critical (Goodrich et al., 1990). Woolhiser et al. (1990) report that among all the parameters that affect the runoff generation in arid regions, the model used is highly sensitive to the rainfall input. Few rain gauges scattered in a catchmnet with daily temporal scale, in the best cases, are not able to catch the temporal and spatial variability of the erratic rainfall in arid regions (Osborm and Renard, 1973; Wheater, 2002). However, in temperate regions where rainfall is uniform in space and has gentle rain intensity with low burst, a standard set of rain gauges can work efficiently (Pilgrim et al., 1988). There are two types of rain gauges: non-recording and recording rain gauges (Sene, 2013). The non-recording rain gauges consist of a funnel, circular rim with 12.7 cm diameter, and a calibrated measuring cylinder to measure the rain depth directly. The non-recording rain gauges should be revisited on a daily basis during the rainy season or several times per day in case of heavy rain storms. Actual reading are taken early in the morning as most of the rain occurs at night in arid areas. The recording gauges have additional device in order to convert rain volume to electric or mechanical signals that can be recorded electronically or mechanically. Example of the mechanical recorder is the grapher, which consists of graph paper fixed on a clock driven drum and pen connected to float unit installed on a small tank at the bottom of the gauge that is used to draw the rain mass curve (Raghunath, 2006).

Developing of an areal rainfall map from a network of rain gauges using statistical methods (arithmetic mean, Thiessen polygon, weighted inverse distance, or other interpolation techniques) represents another challenge for a detailed catchment rainfall representation. The difficulties are due to the high spatial and temporal variability of rainfall under arid environments. This necessitated the development of areal rainfall evaluation techniques. Rainfall measured by radar provides high areal coverage with high temporal and spatial resolutions (Barge et al., 1979). The radar measures the rain by measuring the attenuation to occur to radar signal due to rain drops. This attenuation of the radar power can be directly calibrated using the rain drop size distribution parameters (DSD) (Barge et al., 1979). Although radar is efficient for areal rain evaluation, its initial cost is very high which is not accessible for many countries in arid region. Additionally, there are uncertainties regarding the parameterization of the prevailing size distribution for the raindrops and the relationship between radar reflectivity and rain rate (Krajewski and Smith, 2002).

The recent development in satellite-based rainfall measurement provides an alternative relatively cheaper source of rainfall data which is available freely online. The satellite sensor estimates the rainfall using passive or active type of remote sensing technique (Kumar and Reshmidevi, 2013). The passive one usually estimates rainfall using the top of cloud temperature, so called brightness temperature, which is usually measured in the infrared wavelength range (Hengl et al., 2010). On the other hand, active methods use the microwave and radar techniques to measure the attenuation of the radar power at several heights and then surface rain can be estimated (Skolnik, 1962; Meneghini et al., 1983; Hengl et al., 2010).

1.2. Systems of space-borne rainfall estimation

Several methods have been utilized to estimate the rainfall from space. For example, some methods use the visible portion of the electromagnetic energy to estimate precipitation intensity based on reflectivity of clouds. While the infrared portion of the electromagnetic energy is used to measure the top of the cloud temperature. These satellite-based precipitation products provide an unprecedented opportunity for hydrometeorological applications and climate studies.

The Tropical Rainfall Measuring Mission (TRMM) is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA). The satellite is non sun-synchronous satellite designed for quantitative monitoring of tropical and subtropical rainfall, rain profiles, and brightness temperature (Kidd and Levizzani, 2011). TRMM satellite was launched in November 1997 with a designed orbit

height of 350km, inclination of 35 degrees. In August 2001, the satellite orbit was adjusted to 407km, in order to extend its operational life cycle. The satellite orbits the earth 16 times per day. TRMM started to produce continuous data in December 1997. TRMM is the first meteorological satellites designed for the quantitative estimation of tropical and subtropical rainfall. Operating the satellite in non-sun-synchronous orbit provides the opportunity for taking rainfall measurements during the day (Kidd and Levizzani, 2011). The main purpose of TRMM mission is to understand the global water and energy cycle through the measurement of tropical rainfall and latent heat. The satellite carries five earth observing sensors. Among them, the three rainfall instruments on TRMM are the TRMM Microwave Imager (TMI), Precipitation Radar (PR), and the Visible and Infrared Radiometer System (VIRS). These three rain instruments are providing the most complete rain data up to date.
Accordingly, TRMM provides a comprehensive and radially available rain evaluation data which can be used effectively to study the spatial and temporal distribution of rain in arid areas. The main objective of this study is to validate the satellite-based rainfall measurement by comparing the rainfall data retrieved from satellite with data measured by ground rain gauges in the arid and semi-arid regions of the Sudan. Specifically, the combined monthly rainfall product of TRMM satellite (3B43) will be used as the space-borne rainfall data.

2. MATERIALS AND METHODS

The rainfall data obtained from TRMM multi-satellite data set (combined sensors) have been used in order to validate the potential of satellite data to measure rainfall over arid areas. The ground data used for validation were obtained for 15 stations on the arid and semi-arid regions of the Republic of the Sudan (Figure 1).

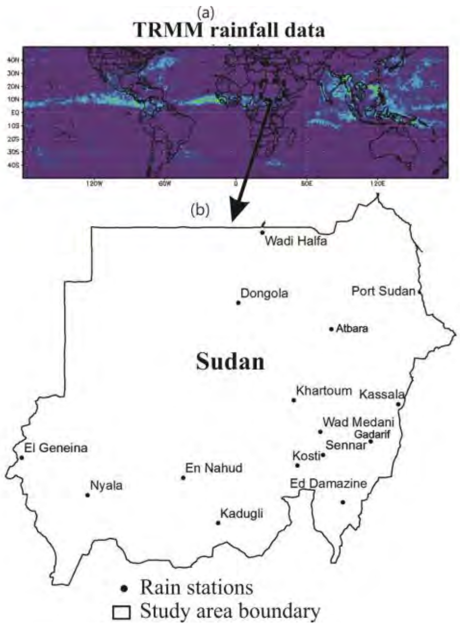

Figure 1. Global cover of TRMM (a) and location of ground rain stations used in the validation of satellite-borne data (b)

The satellite data (3B43) contains monthly combined microwave-IR and surface gauge data in order to estimate precipitation with a global grid resolution of 0.25˚ in the longitudinal and latitudinal directions (Huffman et al., 2007). The 3B43 data is available for the area ranged from 50˚ S to 50˚ N (Figure 1). The data contain the precipitation rate, monthly accumulative rainfall depth, and error estimates. The ground rainfall data was obtained for the area between latitude 10 to 22 and longitude 20 to 40. The data is available freely at the internet (http://disc2.nascom.nasa.gov/Giovanni/tovas/) and the period from January 1998 to December 2010 was considered in the validation procedures. The average annual rainfall ranged from 827 mm in Kadugli at the south of the study area to 1 mm in Wadi Halfa in the north. This variability is only in the range of 1000 km distance. The area can be classified as arid and semi-arid with high desertification vulnerability. Rainfall data in the study area is scarce. Statistical indices have been used to evaluate the matching between the satellite data and ground rain in term of trend and error propagation. Three indices have been used to evaluate the performance of TRMM in estimating rainfall in arid areas which are: the correlation coefficient (r), the mean bias error (MBE) and root mean square error (RMSE).

The MBE and RMSE has been calculated using equation 1, and 2, respectively.

$$\mathrm{MBE} = {}^{1}/_{\mathrm{n}} \sum_{\mathrm{i=0}}^{\mathrm{n}} (\mathrm{SR_i} - \mathrm{GR_i}) \quad (1)$$

$$\mathrm{RMSE} = \sqrt{{}^{1}/_{\mathrm{n}} \sum_{\mathrm{i=0}}^{\mathrm{n}} (\mathrm{SR_i} - \mathrm{GR_i})^2} \quad (2)$$

where SR_i and GR_i are the rain data from satellite and ground, respectively.

Table 1. Overall satellite data validation parameters for the monthly rainfall for the period January 1998 to December 2010 for 15 ground rain gauges.

Stations	Long˚ E	Lat˚ N	r	MBE	RMSE
Khartoum	32.55	15.59	0.92**	2.37	10.24
Wad Madani	33.52	14.40	0.80**	-3.51	34.87
Sinnar	33.57	13.58	0.94**	1.48	19.14
En Nahud	28.43	12.69	0.95**	1.53	15.65
Damazine	34.35	11.77	0.94**	2.10	27.07
Gadarif	35.39	14.03	0.84**	8.80	45.44
Kassala	36.41	15.45	0.94**	0.71	13.16
Atbara	33.99	17.70	0.86**	0.57	6.42
Dongola	30.47	19.17	0.78**	0.75	4.08
Wadi Halfa	31.37	21.79	0.32**	1.27	2.51
Port Sudan	37.22	19.62	0.70**	-0.85	13.87
El-Geneina	22.45	13.45	0.94**	11.87	29.04
Kadugli	29.72	11.02	0.92**	1.75	28.75
Kosti	32.67	13.16	0.91**	2.17	36.30
Nyala	24.88	12.04	0.92**	1.00	22.18

r is a correlation coefficient and P-value between the two practice; MBE is a mean bias error calculated using equation (1); RMSE is the root mean square error calculated using equation (2); ** significant at 0.01 probability level.

3. RESULTS AND DISCUSSION

3.1 Overall performance of TRMM in rainfall measurement

The 3B43 monthly data are significantly correlated to the ground rainfall data over the 15 examined locations (Table 1). The overall average r, MBE, RMSE were 0.85 (P-value <0.001), 2.11, and 20.67 respectively. The highest r was 0.95 at En Nahud station and the lowest r was 0.32 at Wadi Halfa (Table 1). The MBE for the analyzed stations was ranging between -3.51 mm at Wad Madani and 11.87 mm at El-Geneina. These values reflect the range of under- and over estimation. Based on the analyzed study period the errors in the satellite rain estimation ranged between -3.5 to 11.8 mm. Based on the statistics presented on Table (1), the satellite-estimated rainfall is significantly correlated with ground observations.

Generally, the point-to-point results showed good agreement between the satellite and rain gauge monthly data. The errors can be attributed to the nature of the rainfall in such areas. The relationships between the two rainfall sources for four representative stations are shown in figure (4). While the correlation coefficient is a major indicator of the potential of satellite, the MBE and RMSE represent the degrees of error in in the estimated data. The mean bias error (MBE) ranged between -3.5 mm in Wad Madani station at central Sudan and the maximum was 11.87 mm at El-Geneina in the western part of Sudan. The MBE error also did not show any spatial trend. The root mean square error was used as average error indicator; which ranged between 2.51 and 45.44 mm. This magnitude of error is generally acceptable in arid areas where the inter- and intra-annual variability is very high.

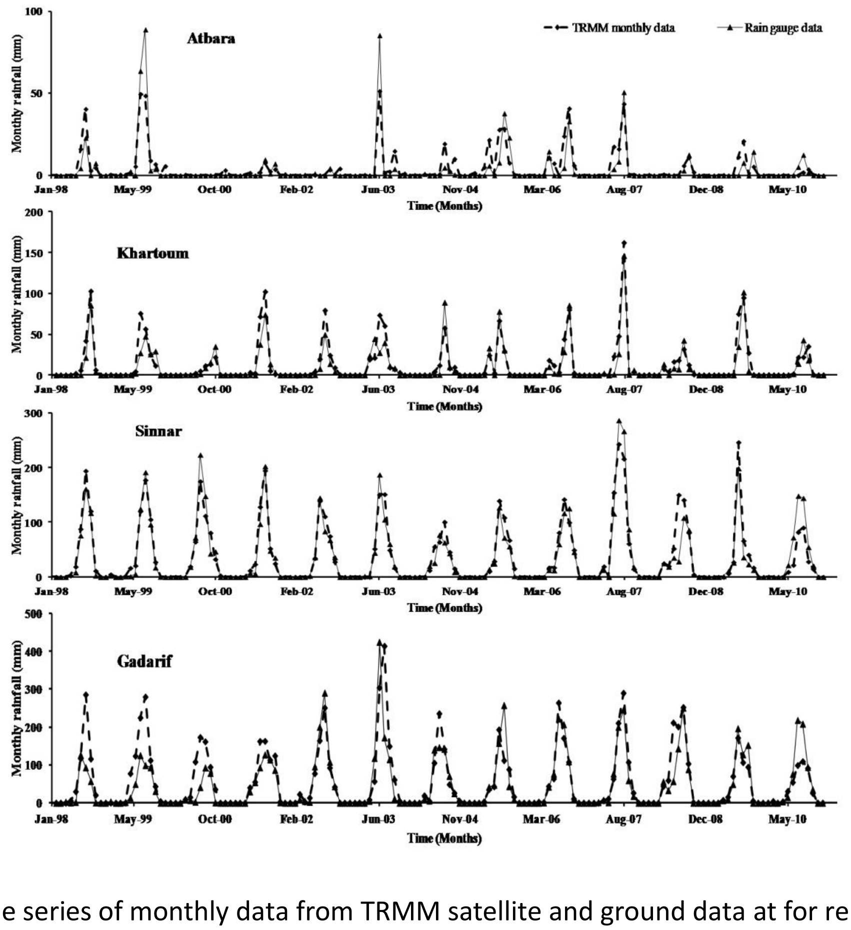

Figure 2. Time series of monthly data from TRMM satellite and ground data at for representative stations

3.2 Performance of TRMM in temporal rainfall measurements

The time series of the estimated rainfall from TRMM and the ground data showed general agreement with some under- and over-estimation during months of high rainfall (Figure 2). The satellite data and ground data for the period from January 1998 to December 2010 showed good agreement at the four selected stations. The stations represent the hyper-arid north to the relatively humid south of the Republic of Sudan (Figure 2). There is some underestimation for the rainfall in the stations located in the arid areas (Atbara and Khartoum) and overestimation for the stations located in the semi-arid areas (Sinnar and Gadarif).The four representative stations, Atbara, Khartoum, Sinnar, and Gadarif, showed correlation coefficient ranging between 0.94 in Sinnar and 0.84 in Gadarif. In general, the 3B43 monthly data was significantly correlated to the ground rainfall data at the 15 examined locations (Table 2). The maximum correlation was 0.95 at En Nahud station and the minimum correlation was at Wadi Halfa station (annual rainfall < 5 mm).

3.3 Performance of TRMM in spatial rainfall measurement

The main advantage of the satellite data is that it provides spatially distributed rainfall data that cannot be achieved using ground rain gauges. The rainfall distribution results are shown in Figure (4). The results show good agreement between the satellite and ground rainfall data. The agreement can be noticed form the matching between the isohyets lines (ground data) and spatially distributed rainfall surface achieved from satellite.

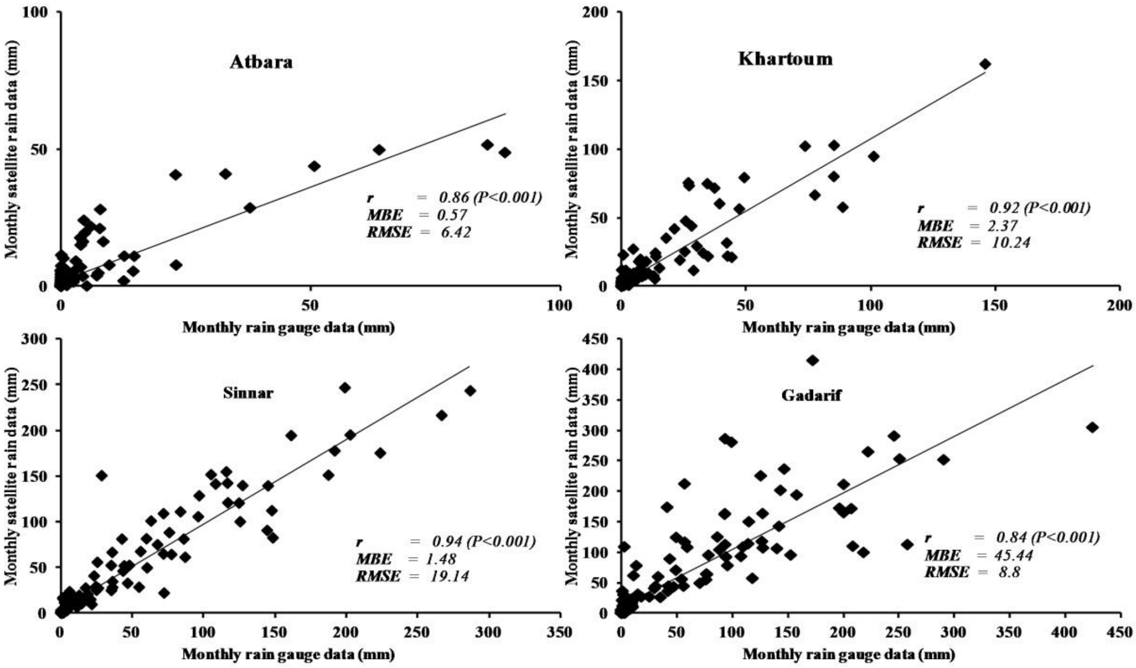

Figure 3. Relationship between TRMM 3B43 monthly data and ground data at Atbra, Khartoum, Sinnar, and Gadarif stations.

3.4 Performance of TRMM in rainfall measurement during the rainy season

The monthly statistical parameters showed significant agreement between the satellite data and ground rainfall during the rainy season (Table 2). The data of Port Sudan has been excluded because the area has a winter rainfall season that extends from November to April. However, some cases may occur during a very wet rainy season where the inter-tropical convergence zone reach to the top north of Sudan or latitude 22˚N (Fontaine et al., 2011).
The validation indicators showed high variability when assessed during the rainy months only (Table 1). The average r ranged between 0.62 (P-value <0.001) during June and 0.73 in October. Whilst the average is relatively low yet some stations show very high correlation such as Kassala in June (0.99) and Dongola in July (0.96). Considering the MBE and the RMSE, the performance of the satellite rainfall data was better during the rainy season peak which occur during July and August (Table 2).

Table 2. Monthly performance of the satellite data in compare to ground data during the rainy season in Sudan.

Stations	June			July			August			September			October		
	r	MBE	RMSE	r	MBE	RMSE	r	MBE	RMSE	r	MBE	RMSE	r	MBE	RMSE
Khartoum	0.60	7.91	2.81	0.79	53.40	7.31	0.89	30.12	0.18	0.95	8.47	2.91	0.87	3.58	1.89
Wad Madani	0.31	3.31	17.60	0.53	4.78	23.93	0.61	2.66	3.40	-0.04	2.02	11.09	0.66	1.00	4.93
Sinnar	0.82	1.32	6.22	0.74	2.98	13.64	0.84	2.77	3.34	0.79	1.20	5.22	0.84	0.59	2.38
En Nahud	0.92	1.50	7.05	0.83	1.73	8.51	0.87	2.38	8.96	0.90	1.19	4.82	0.77	0.71	3.70
Damazine	0.67	2.82	13.58	0.81	2.32	9.67	0.63	4.20	16.49	0.79	2.50	11.15	0.72	1.05	4.76
Gadarif	0.03	3.53	17.56	0.52	5.42	22.27	0.03	7.10	33.06	0.26	2.16	9.46	0.83	1.24	6.23
Kassala	0.99	0.60	3.78	0.87	1.31	6.53	0.85	1.77	8.12	0.67	1.03	6.78	0.74	0.27	1.24
Atbara	0.83	0.18	1.33	0.91	0.68	3.68	0.81	0.89	4.36	0.87	0.26	1.52	0.30	0.31	1.51
Dongola	0.20	0.02	0.14	0.96	0.17	1.07	0.72	0.49	3.88	0.41	0.09	0.66	0.54	0.02	0.07
Wadi Halfa	0.00	0.03	0.14	0.00	0.20	1.43	0.45	0.25	1.38	0.07	0.13	0.63	0.00	0.18	0.87
Port Sudan	0.46	0.12	1.02	0.46	0.47	2.57	0.88	0.24	1.02	0.00	0.38	2.69	0.97	0.34	2.73
El-Geneina	0.37	1.65	7.06	0.48	4.55	20.96	0.69	4.31	17.07	0.86	1.55	6.14	0.92	0.84	3.77
Kadugli	0.72	2.13	8.40	0.59	2.99	13.15	0.77	2.96	14.76	0.38	2.84	13.35	0.81	1.80	11.01
Kosti	0.91	0.90	4.43	0.79	2.22	9.96	0.60	3.94	17.80	0.82	1.53	6.56	0.77	0.53	2.33
Nyala	0.69	1.93	9.31	0.49	2.93	13.02	0.83	2.14	9.98	0.64	1.92	9.32	0.76	0.80	4.19

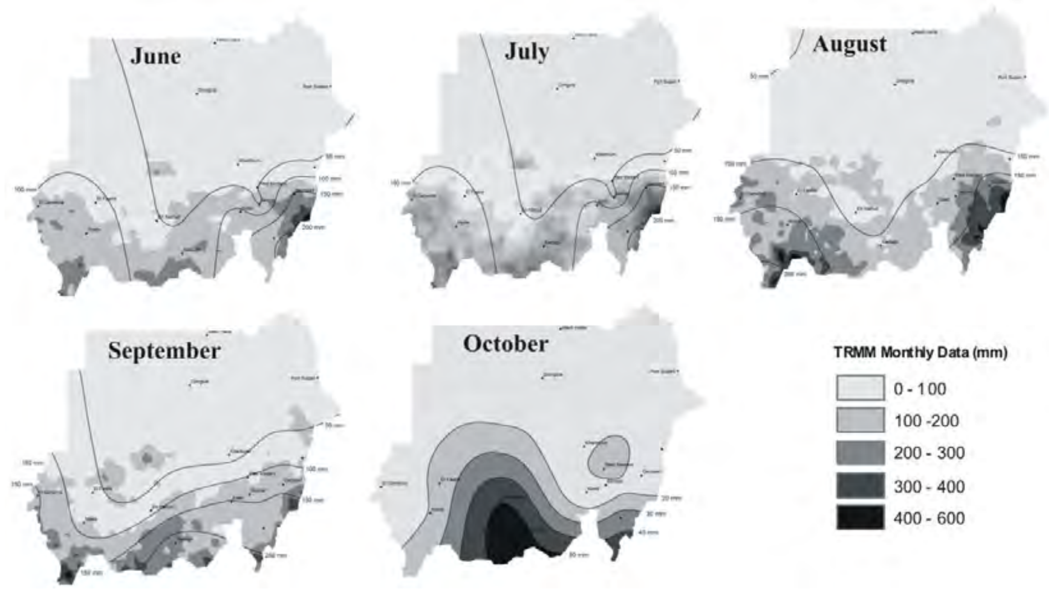

Figure 4. The spatial distribution of TRMM rainfall compared to ground monthly rainfall data (isohyets).

4. CONCLUSIONS

A high percentage of the population in arid and semi-arid regions is mainly reliant on rainfall for their daily life consumption and food production. Rainfall data in these areas are highly scarce. One of the major problems in arid areas in the localized nature of rainfall storms, especially during the summer season which makes any number of gauges not really efficient to detect such storms. In this study the potential of using satellite data in arid areas have been highlighted. Data obtained from TRMM sensors have been examined. Monthly data obtained from combined sensors and ground gauges have been compared with ground measurements. The results show good agreement between the satellite data and ground rainfall points. There is therefore great promise for the use of TRMM sensors for estimating rainfall in arid and semi-arid regions of the Sudan.

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