

## Evaluation of five Satellite Based Precipitation Products over Côte d'Ivoire from 2001 to 2018

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### ABSTRACT

Since gauges provide only point measurements, practical limitations are the installation and maintenance of a dense gauge network in areas that are difficult to access, such as mountains, deserts, forests and large water bodies. For over thirty years, meteorological satellites have provided an alternative to monitor the spatial and temporal distributions of precipitation. This study aims to assess the errors associated with satellite estimation data in Côte d'Ivoire. We investigated five satellite precipitation products: TAMSAT v.2, TAMSAT v.3, RFE 2.0, ARC 2.0 and TRMM 3B42 v.7. The satellite-based products performance was evaluated at daily, monthly, seasonally and annual scale from 2001 to 2018 using 19 weather stations. This validation was carried out using continuous statistics ( $R$ ,  $R^2$ , RMSE and NSE) and categorical statistics (POD, FAR, FBI, HSS, HKSS and ETS). The results showed that as time steps are increased, performance improves with all products. Thus, TAMSAT v.3 and TRMM 3B42 v.7 perform better on monthly, seasonal and annual scales. ARC 2.0 and RFE 2.0 remain efficient at all scales and more precise at large scales. TAMSAT v.2 performs less well than all other products but remains acceptable. The quality of the different products has a North-South gradient. They perform better in Northern and Center zones than in Southern.

**Key words:** ARC 2.0, RFE 2.0, TAMSAT 2.0, TAMSAT v.3, TRMM 3B42 v.7

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### I. INTRODUCTION

Precipitation has a very high socio-economic impact, particularly in areas where water resources are scarce. With the increase in world population and the emerging effects of climate change, the pressure on water resources is stronger than ever. Côte d'Ivoire economy depends mainly on agricultural products like cocoa. However, because of the lack of irrigation schemes, Ivorian agriculture is subject to vagaries of rainfall variability. The changes in rainfall also have serious consequences on river flows, on which depend country's many hydropower projects. Hydrological models developed to predict river flows for flood forecasting and for dam designs require rainfall data acquired at high spatial and temporal resolutions. The same can be said for better drought forecasting for agricultural purposes [1, 2, 3, 4-5]. High spatial and temporal variability of precipitation directly affects the agricultural calendar and can lead to unexpectedly heavy drops in yields. Changes in the starting date of the rainy season may force the cultivator to sow a different type of seed and thus his final yield. Reliable weather estimates with high spatial and temporal resolution may help predict better the starting date of the rains. Normally, climate studies in literature focus on seasonal or monthly cumulative rainfall registered by rain gauges. Rain gauge data may conceal local rainfall disparities if the gauge network is not sufficiently dense. In Côte d'Ivoire, the number of installed rain gauges is insufficient for a reliable assessment of local variations and extreme events. At present, only 189 weather stations and 14 synoptic stations exist, and they are concentrated in the southern part of the country [6]. The northern region, which is suffering greatly from changes in rainfall patterns, has very few weather stations. In addition, currently, transmission of rain gauge data cannot be handled in real-time, an operational necessity for optimal decision making. It is also worth highlighting the breakdown of data collection during the military-political crisis in Côte d'Ivoire from 2002 to 2011. On the other hand, the existing stations can provide the historical knowledge, which can serve as a benchmark for calibrating other types of rainfall estimates. In regions that have low or unreliable

rain gauge coverage, meteorological satellites can provide rainfall estimates, with a wide spatial coverage and a temporal frequency up to twice per hour [7, 3, 8,9,10,11,12,13-14,15,16]. This data is easily and freely available in near real time. However, satellite precipitation estimates are indirect and hence suffer from significant errors in sensor calibration [17, 16] and in sampling. In addition, about 80% of the infrared-based data are affected by cloud cover, so it is essential to develop mechanisms to assimilate such data [18]. The early meteorological satellites have large errors in their estimates, but their high temporal and spatial coverage over a long period provides a base to calibrate them using rain gauge information from areas with a dense gauge network. The newer satellites provide better technology to understand the rain cloud formation but at low temporal and spatial coverage. The data from both satellite types can be compared, along with ground data, so that recent satellite data can also be used in long-term rainfall variability. Proper understanding of hydro-climatic variability at different temporal and spatial scales when using the satellite and its translation towards efficient use of water resources is the central theme of this research.

## II. MATERIAL AND METHODS

### 2.1. Study area

The study area is the entire country of Côte d'Ivoire, located between Longitudes 2° 30' and 8° 30' W and Latitudes 4° 30' and 10° 30' N with an area of 322 462 km<sup>2</sup>, covering about 1% of the African continent. It is a part of West Africa, shares borders with Liberia and Guinea to the West, Mali and Burkina Faso to the North and Ghana to the East. To the South, Atlantic Ocean has a 550 km long coastline (fig. 1).

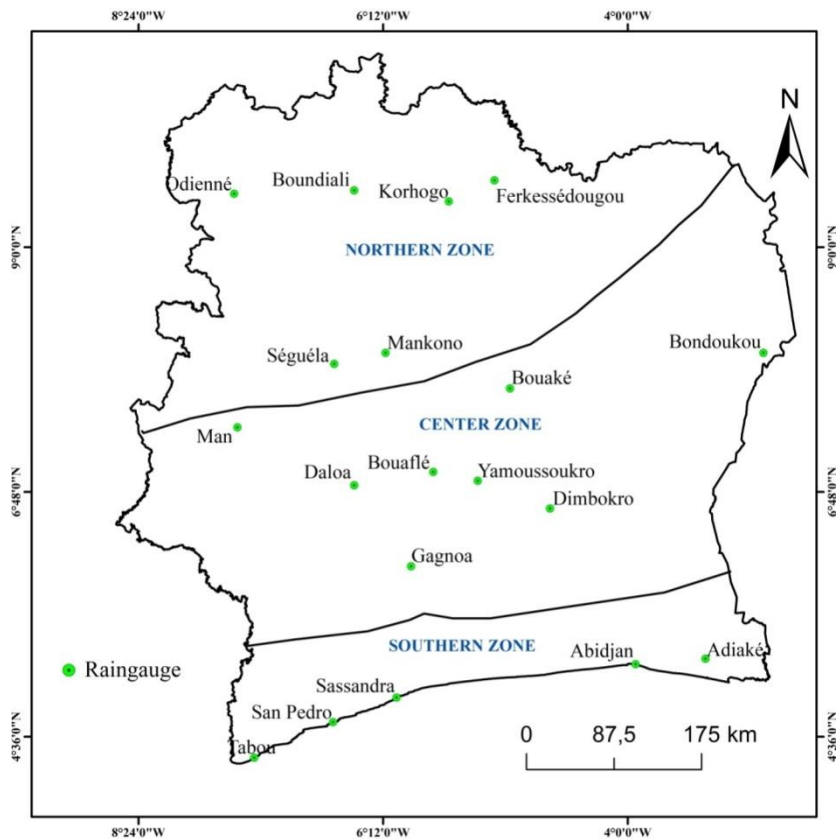


Fig. 1: Study area, distribution of the rain gauges used and climatic division; adapted from [19-21]

### 2.2. Rain gauges data

Daily precipitation data from 19 gauging stations provided by SODEXAM (Société de Développement et d'Exploitation Aérienne, Aéroportuaire et Météorologique) was selected for this study because of the continuity of the recording from 2001 to 2018 (table 1 and fig. 1). Fig. 1 presents the breakdown of the climatic zones of the Côte d'Ivoire deduced from the Principal Component Analysis of Varimax type [19-21] and the rain gauges used for the study. This breakdown shows three zones: the northern zone of Côte d'Ivoire, the central zone and the southern zone, bordering the Gulf of Guinea [19-21]. The gauging stations have been grouped together for the analysis according to this climatic breakdown (Fig. 1):

- The weather stations of Odienné, Boundiali, Korhogo, Ferkessédougou, Mankono and Séguéla are in Northern zone with a unimodal rainfall regime with a maximum in August;
- The weather stations of Bouaké, Dimbokro, Daloa, Yamoussoukro, Gagnoa, Man, Bouaflé and Bondoukou in the Center zone where the regime is bimodal with less pronounced maximums in June and September;
- The weather stations of Abidjan, Adiaké, Sassandra, San Pedro and Tabou in southern zone with a bimodal regime with a peak rainfall in June and a less pronounced maximum in October.

**Table 1:** Nineteen rain gauge across Côte d'Ivoire

Station name	Long (°)	Lat (°)	Station name	Long (°)	Lat (°)
Korhogo	-5,61	9,41	Bondoukou	-2,78	8,05
Odienné	-7,54	9,48	Yamoussoukro	-5,35	6,9
Boundiali	-6,46	9,51	Dimbokro	-4,7	6,65
Man	-7,51	7,38	Adiaké	-3,3	5,3
Séguéla	-6,64	7,95	Abidjan	-3,93	5,25
Gagnoa	-5,95	6,13	Sassandra	-6,08	4,95
Mankono	-6,18	8,05	San-Pedro	-6,65	4,73
Bouaké	-5,06	7,73	Tabou	-7,36	4,41
Daloa	-6,46	6,86	Ferkessédougou	-5,2	9,6
Bouaflé	-5,75	6,98			

### 2.3. Precipitation products

In this work, we investigated five satellite precipitation products: namely TAMSAT v2 and TAMSAT v.3 developed by the University of Reading of the United Kingdom; TRMM 3B42 v.7 developed by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) [3, 8]; RFE 2.0 (RainFall Estimation) and ARC 2.0 (Africa Rainfall Estimate Climatology version 2) developed at the Climate Prediction Center (CPC). They cover the whole of West Africa.

A brief description of each algorithm is given below. All the popular open access rainfall products for Côte d'Ivoire will be explained one by one, because all the developers use different types of algorithms and combine different type of data from satellites and ground measurements to come up with a rainfall estimate. Their databases will be calibrated for Côte d'Ivoire using historical rain gauge data over the period 2001-2018.

#### 2.3.1. Tropical Application of Meteorology using Satellite and other data (TAMSAT v.2 and TAMSAT v.3)

The TAMSAT algorithm was developed to provide rainfall estimates for drought and famine warning for Africa. It is used by a number of meteorological services in African countries and by FAO for their regional drought monitoring program [22]. The TAMSAT Group has, since the 1980s, produced estimates at the 10-day (dekad) scale.

In January 2017, the TAMSAT Group released the two version based on high resolution Meteosat thermal-infrared (TIR) observations for all of Africa, available from 1983 to the present and updated in near-real time. TAMSAT v.2 and TAMSAT v.3 are based on the disaggregation of the TAMSAT version 2.0 dekadal [24], and TAMSAT version 3.0 pentadal rainfall estimates respectively, to a daily time-step using daily calibrated cold cloud duration (CCD) observations. The characteristics of the data are presented in Table 2.

The algorithm described in [23], [22] and [24], is based on the principle of the use of METEOSAT Thermal Infrared images allowing to monitor the tops of cold clouds of rainy convective systems of cumulonimbus types which constitute a useful indicator for rainfall in the tropics. The data are obtained every 15 minutes from July 2006 and every 30 minutes before that date [25] and is then calibrated with ground observations. With a spatial resolution of 0.0375° (4 km), available for all of Africa from 1983 up to now, free of charge, on the TAMSAT group site of the University of Reading at the United Kingdoms: <http://www.met.rdg.ac.uk/~tamsat/>.

#### 2.3.2. Rainfall Estimation version 2 (RFE 2.0)

Rainfall Estimation is produced by the Climate Prediction Center through the Famine Early Warning System Network (FEWS NET), a member of the US National Oceanic and Atmospheric Administration (NOAA) agency. Beginning January 1, 2001, the African Rainfall Estimation Algorithm Version 2.0 (RFE2.0) replaced the previous algorithm RFE 1.0 used from June 1, 1995 to December 31, 2000. The RFE 2.0 algorithm linearly combines satellite precipitation estimates with in situ estimates. A weight is assigned to each data item on the basis of its error relative to the in situ data. The second step is to reduce rainfall bias estimated at the end of the first stage. The MW measurements are derived from the SSMI and AMSU-B data [27, 28]. The IR satellite estimates are derived from the GPI (GOES Precipitation Index), based on measurements of the METEOSAT IR imagers. In situ data are taken from the CPC's daily database. RFE 2.0 is a real-time product

specific to the African continent with a spatial resolution of 0.1° and a temporal resolution of 24 hours (table 2). It is freely available on this web:

[Http://www.cpc.ncep.noaa.gov/products/fews/RFE2.0\\_tech.pdf](http://www.cpc.ncep.noaa.gov/products/fews/RFE2.0_tech.pdf)

### 2.3.3. Africa Rainfall Estimate Climatology version 2 (ARC 2.0)

The Africa Rainfall Climatology (ARC1) has the same algorithm as the RFE 2.0. The only difference is that the passive microwave sensors are not used [29-30]. This makes it possible to derive a rainfall estimate for a much longer period, namely from 1983 till present. ARC 2.0 is the improved version and uses recalibrated IR imagery. Three (3) hourly geostationary IR data centred over Africa from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and quality controlled GTS gauge observations reporting 24 hours rainfall accumulations over Africa (table 2). This makes it possible to obtain high resolution historical rainfall estimations and allows users to see rainfall phenomena on local scales. The ARC 2.0 method only uses the GPI (GOES Precipitation Index) and the GPCC datasets. Those datasets are reliable and has a better coverage than passive microwave data. The disadvantage of the exclusion of the passive microwave rainfall estimations is that it tends to lead to a failure in capturing the locally heavy precipitation events [31].

### 2.3.4. Tropical Rainfall Measuring Mission (TRMM 3B42 v.7)

Since its launch in 1997, TRMM has provided precipitation measurements in tropical and subtropical regions of the world. TRMM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA) designed to monitor and study tropical rainfall. The TRMM Micro Imager (TMI) measures the microwave energy emitted by the Earth and the atmosphere to quantify water vapor, cloud water and the intensity of precipitation in the atmosphere. The Rainfall Radar can see through the precipitation column, offering new perspectives on the structure of the tropical storm and its intensity. Estimates are provided on a 0.25° x 0.25° grid within the 50° S-50° N latitude band, for the period 1998 to present (table 2). The data provided by algorithm 3B42, combining syntheses of microwave images TRMM and other satellite is, at present, one of the best products available at this spatial resolution. The microwave sensors of the AQUA and NOAA (National Oceanic and Atmospheric Administration) satellites, the Defense Meteorological Satellite Program (DMSP) and the visible/infrared geostationary satellite data are taken into account in the above algorithm [3]. These estimates are then adjusted by incorporating the monthly climatic measurements of the GPCP and CAMS (Climate Assessment and Monitoring System) networks to give the daily TRMM 3B42 v.7 products.

**Table 2:** Information of the five satellite products used in this study

Satellite data	Temporal Coverage	Spatial Coverage	Spatial Resolution	Developer	Data format	Temporal resolution
TAMSAT v.2	1983-present	Africa 38° N-36°S, 19°W-52°E	0.0375° (~4 km)	Univ. of Reading (UK)	NetCDF	Daily
TAMSAT v.3	1983-present	Africa 38° N-36°S, 19°W-52°E	0.0375° (~4 km)	Univ. of Reading (UK)	NetCDF	Daily
RFE v.2	2001-present	Africa 43.7°N-42.2°S, 23.5° W-63.4° E	0.1° (~10 km)	NOAA (CPC)	NetCDF	Daily
ARC 2.0	1983-present	Africa 40°N – 40°S, 20°W – 55°E	0.1°(~10km)	NOAA (CPC)	NetCDF	Daily
TRMM 3B42 v.7	1998-present	50° S-50° N	0.25° (27.8 km)	NASA/JAXA	NetCDF	Daily

## 2.4. Methodologies for the assessment of the precipitation products

### 2.4.1. Statistical validation

The accuracy of each precipitation product was assessed at daily, monthly, seasonal, and annual time scales by comparing satellite rain data with ground observations using 19 rain gauges based on the availability of the different products.

#### 2.4.1.1. Categorical statistics

This comparison is based on a contingency table to inform on the reliability of the reference data and on the influence of the sensitivity of the satellite products to the detection of the occurrence of precipitation (Table 3). The four elements of the contingency table are: Correct negatives A: is the number of occasions when both gauge records zero rain and satellite estimates is zero; False alarms B: is the number of occasions when gauge records zero but there is some satellite estimates; Misses C: is the number of occasions when gauge records some rain but satellite rainfall is zero; Hits D: is the number of occasions when gauge records and satellite estimates values are non-zero.

**Table 3:**Contingency table used for the statistical analysis of rainfall occurrence for the satellite rainfall estimates

	<i>Gauge observations</i>	
	No Rain	Rain
<i>Satellite rainfall estimate</i>	No Rain A	Rain C
	Rain B	D

From this contingency table, six indicators are calculated:

- Probability of detection (POD) is between 0 (no detection) and 1 (perfect detection) (equation 1).

$$POD = \frac{D}{C + D} \quad (1)$$

- False detection ratio (FAR) equal to 0 is equivalent to a perfect estimate by the satellite product. (Observation fraction of days without rain as rainy days) (Equation 2).

$$FAR = \frac{B}{B + D} \quad (2)$$

- Frequency bias index (FBI) is between 0 and + ∞ (if FBI = 1, then the estimate is ideal, FBI<1: underestimation, FBI> 1: over estimation). (Ratio of estimated rain days and days when no rain is observed)[16,25].

$$FBI = \frac{B + D}{C + D} \quad (3)$$

-Heidke skill score (HSS):((-∞; 1], HSS= 1: perfect; HSS=0: No skill) (equation 4).

$$HSS = \frac{2(AD - BC)}{(A + B)(B + D) + (C + D)(A + C)} \quad (4)$$

-Hanssen–Kuipers skill score (HKSS) (equation 5): ([-1; 1]; HKSS=1: perfect; HKSS=0: No skill).

$$HKSS = \frac{AD - BC}{(A + B)(C + D)} \quad (5)$$

- Equitable threat score (ETS)(equations 6 and 7): ([- $\frac{1}{3}$ ; 1]; ETS < 0: No skill).

$$ETS = \frac{D - D_R}{B + C + D - D_R} \quad (6) \quad \text{Where } D_R = \frac{(C + D)(B + D)}{A + B + C + D} \quad (7)$$

### 2.4.1.2. Continuous statistics

Several authors used statistical criteria for the verification of quantitative estimates of satellite precipitation [32, 16]. Pearson correlation coefficient R, Root Mean Square Error (RMSE), the coefficient of determination R<sup>2</sup> and Nash–Sutcliffe efficiency(NSE) are commonly used.

The Pearson correlation coefficient (R) [0; 1] (equation 8):

$$R = \frac{\sum(G - \bar{G})(S - \bar{S})}{\sqrt{\sum(G - \bar{G})^2} \cdot \sqrt{\sum(S - \bar{S})^2}} \quad (8)$$

G = Gauge measurement

S = Satellite rainfall estimate

$\bar{G}$  = Average of gauge measurement

$\bar{S}$  = Average satellite rainfall estimate

The coefficient of determination R<sup>2</sup> is between 0 and 1, (Equation 9):

$$R^2 = \frac{[\sum_{i=1}^n (S - \bar{S}) \cdot (G - \bar{G})]^2}{\sum_{i=1}^n (S - \bar{S})^2 \cdot \sum_{i=1}^n (G - \bar{G})^2} \quad (9)$$

The Nash–Sutcliffe efficiency (NSE) is between 0 and 1. If the NSE = 1, then the estimation is perfect and NSE= 0 signifies no better performance than using the mean of the gauged data (equation 10).

$$NSE = 1 - \frac{\sum_{i=1}^n (S - G)^2}{\sum_{i=1}^n (G - \bar{G})^2} \quad (10)$$

Root Mean Square Error (RMSE) varies from [0, + ∞ [(equation 11).



$$RMSE = \sqrt{\frac{\sum_{i=1}^n (S-G)^2}{n}} \quad (11)$$

### III. RESULTS AND DISCUSSION

#### 3.1. Mean daily rain detection ability assessment

Tables 4, 5 and 6 show the categorical statistics of satellite rain products at the various weather stations. The probability of detection (POD) of the products is higher in the Northern and Center zones than in Southern. Thus at the stations of Mankono, Boundiali, Ferkessédougou, Séguéla, Bouaké and Bouaflé the PODs reach 100% (Tables 4 and 5). At the Adiaké and Tabou weather stations TAMSAT v.2, TAMSAT v.3 and TRMM 3B42 v.7 have PODs less than 50%. In general, ARC 2.0 and RFE 2.0 have the highest scores in the Center and Southern zones (Tables 5 and 6).

Significant false detections (FAR) are observed at the weather stations in Northern and Central zones (Tables 4 and 5) than in Southern zone. These differences may be explained by the origin of precipitation with convective weather systems (which dominate during rainy periods) being more accurately detected by satellite sensors [33]. FAR greater than or equal to 50% is noted at Bouaflé and Dimbokro for all products (table 5). At Mankono we note 56%, 51% and 50% respectively for TAMSAT v.3 and RFE 2.0, TRMM 3B42 v.7 and Séguéla 54% for TAMSAT v.3. No false alarm detected at certain stations in the Central and Northern zones such as Bouaké, Boundiali, Ferkessédougou and Mankono for ARC 2.0. TAMSAT v.3 and RFE 2.0 products recorded low scores (around 0.04) at Odienné weather station (Table 4).

The frequency bias indices (FBI) are less than 1 at the stations of Southern zone where ARC 2.0 and RFE 2.0 have the highest scores (from 0.79 to 0.95) (Table 6). This reflects an underestimation of rains. No bias was found for RFE 2.0 and TAMSAT v.3 respectively at the Gagnoa and Yamoussoukro weather stations in the Central zone (FBI = 1) (Table 5).

Bias greater than 1 are observed with 2.29 and 2.05 respectively for TAMSAT v.3 and RFE 2.0 at Mankono and 2.16 for TAMSAT v.3 at Séguéla. It means a slight overestimates of rain except ARC 2.0 product, which shows perfect performance with FBIs equal to 1 in Boundiali, Ferkessédougou, Mankono (Table 4). This overestimation can be the result of the sensors' inability to differentiate between drizzly days and rainy days as their spatial scales are much larger than the point locations of rain gauges [34, 35].

All of these products have the HSS from 45 to 96% except at the weather stations of Abidjan, San Pedro, Sassandra and Tabou where HSS are below 20% for TRMM 3B42 v.7, TAMSAT v.2 and TAMSAT v.3 (table 6). ARC 2.0 product is distinguished from other data with higher HSS equal to 1 in Boundiali, Ferkessédougou and Mankono (Table 4). ARC 2.0 and RFE 2.0 have the highest HSS across the study area.

Rainy events are well distinguished from non-rainy events for all data, except for Abidjan weather station where TRMM 3B42 v.7 records poor performance (HKSS = 0.24) (Table 6). The HKSS are greater than 50% across all the rain gauges. RFE 2.0 and ARC 2.0 products have the highest HKSS ranging from 50 to 87% except at San Pedro where HKSS equal to 35% for the RFE 2.0 (Table 6). ARC 2.0 discriminates rainy events with a score of 100% in Boundiali, Ferké, Mankono (Table 4).

The ETS are positive (ETS > 0) but the number of correctly adjusted rain events remains low. Generally, RFE 2.0 and ARC 2.0 have the highest scores across the study area. ARC 2.0 records scores of around 100% in Mankono, Boundiali and Ferkessédougou (Table 4).

We observe that the POD, FBI, HSS, HKSS and ETS degrade significantly from Northern zone to Southern zone. In general, satellite estimation products tend to overestimate rainfall in Northern and Centre zones, but there is a good estimate in these zones than in Southern zone. This could be related to the fact that the products better quantify low intensity precipitation. [35] also note that RFE and TAMSAT overestimated low rainfall values and underestimated high values. Previous studies [36, 37] also note that TRMM 3B42 was better at reporting the occurrence of rainfall than the amounts. This low performance of TRMM 3B42 v.7 could also be due to the fact that most of the Microwave (MW) techniques rely indeed on high frequencies ( $\geq 85$  GHz), which are more adapted to ice particle detection than to liquid water over a land area, thus explaining why MW satellites miss most of the warm and light precipitation events [38]. We note, however, an improvement in the false detection ratios (FAR) of the satellite products when we approach the coast in southern zone where the products also tend to underestimate the precipitation. RFE 2.0 and ARC 2.0 (better performing) stand out from the other products, which can be explained by the integration of GPCC observation measures in the implementation of these data carried out by NOAA.

The spatial distribution of the Probability of Detection (POD) of the five products used over the period from 2001 to 2018 is presented in Fig. 2. The different satellite precipitation products present the best PODs in Northern of the study area, except TAMSAT v.2 product and these PODs decrease as we approach the coast

(Fig. 2). We found a greater difference between the ground data and the satellite estimates in the coastal zones against the inland, presumably depending on the nature of the convective fall which is rapid, intense and localized [39].

**Table 4:** Overall rain-detection capability of each precipitation product from 2001 to 2018 over Ferkessédougou, Korhogo, Boundiali, Mankono, Séguéla and Odienné weather stations

STATIONS	SATELLITE DATA	INDICATORS					
		POD [-1; 1] 1=bon	FAR 0=bon	FBI [0; +∞ [ 1=bon	HSS ]-∞; 1] 1=bon	HKSS [-1; 1] 1=bon	ETS [- $\frac{1}{3}$ ; 1] >0 (bon)
<b>Mankono</b>	TAMSAT v.2	0,86	0,35	1,33	0,64	0,71	0,47
	TAMSAT v.3	1	0,56	2,29	0,35	0,50	0,22
	RFE 2.0	1	0,51	2,05	0,44	0,59	0,28
	ARC 2.0	1	0	1	1	1	1
	TRMM 3B42 v.7	0,94	0,50	1,88	0,39	0,58	0,29
<b>Korhogo</b>	TAMSAT v.2	0,55	0,13	0,64	0,40	0,43	0,25
	TAMSAT v.3	0,83	0,23	1,08	0,48	0,47	0,32
	RFE 2.0	0,94	0,23	1,22	0,57	0,54	0,40
	ARC 2.0	0,86	0,16	1,03	0,62	0,62	0,45
	TRMM 3B42 v.7	0,80	0,23	1,05	0,45	0,44	0,29
<b>Boundiali</b>	TAMSAT v.2	0,65	0,25	0,87	0,53	0,52	0,36
	TAMSAT v.3	1	0,44	1,78	0,45	0,52	0,29
	RFE 2.0	1	0,36	1,56	0,59	0,66	0,42
	ARC 2.0	1	0	1	1	1	1
	TRMM 3B42 v.7	0,91	0,45	1,65	0,41	0,46	0,26
<b>Ferkessédougou</b>	TAMSAT v.2	0,69	0,27	0,95	0,54	0,54	0,37
	TAMSAT v.3	1	0,44	1,78	0,45	0,53	0,29
	RFE 2.0	1	0,44	1,78	0,45	0,53	0,29
	ARC 2.0	1	0	1	1	1	1
	TRMM 3B42 v.7	0,91	0,40	1,52	0,49	0,54	0,33
<b>Séguéla</b>	TAMSAT v.2	0,77	0,30	1,11	0,62	0,64	0,45
	TAMSAT v.3	1	0,54	2,16	0,38	0,51	0,23
	RFE 2.0	1	0,44	1,78	0,58	0,71	0,38
	ARC 2.0	1	0,05	1,05	0,96	0,97	0,92
	TRMM 3B42 v.7	1	0,48	1,94	0,47	0,60	0,31
<b>Odienné</b>	TAMSAT v.2	0,81	0,16	0,96	0,70	0,69	0,53
	TAMSAT v.3	0,63	0,04	0,66	0,53	0,89	0,34
	RFE 2.0	0,58	0,04	0,61	0,44	0,53	0,28
	ARC 2.0	0,72	0,28	1	0,52	0,52	0,35
	TRMM 3B42 v.7	0,60	0,28	0,83	0,34	0,37	0,23

**Table 5:** Overall rain-detection capability of each precipitation product from 2001 to 2018 over Man, Bouaké, Bondoukou, Daloa, Bouaflé, Yamoussoukro, Dimbokro and Gagnoa weather stations

STATIONS	SATELLITE DATA	INDICATORS					
		POD [-1; 1] 1=bon	FAR 0=bon	FBI [0; +∞ [ 1=bon	HSS ]-∞; 1] 1=bon	HKSS [-1; 1] 1=bon	ETS [- $\frac{1}{3}$ ; 1] >0 (bon)
<b>Man</b>	TAMSAT v.2	0,71	0,04	0,74	0,65	0,94	0,56
	TAMSAT v.3	1	0,14	1,17	0,79	0,77	0,65
	RFE 2.0	0,97	0,23	1,26	0,63	0,60	0,44
	ARC 2.0	0,86	0,03	0,88	0,80	0,82	0,67
	TRMM 3B42 v.7	0,82	0,28	1,15	0,40	0,40	0,27
<b>Bouaké</b>	TAMSAT v.2	0,76	0,07	0,82	0,78	0,74	0,64
	TAMSAT v.3	0,94	0,27	1,29	0,74	0,80	0,58
	RFE 2.0	1	0,39	1,65	0,62	0,75	0,45
	ARC 2.0	0,82	0	0,82	0,87	0,82	0,77
	TRMM 3B42 v.7	0,94	0,27	1,29	0,74	0,80	0,58
<b>Bondoukou</b>	TAMSAT v.2	0,72	0,10	0,80	0,68	0,66	0,52
	TAMSAT v.3	0,96	0,35	1,48	0,52	0,55	0,35
	RFE 2.0	0,96	0,23	1,26	0,71	0,73	0,55
	ARC 2.0	0,96	0,19	1,18	0,77	0,78	0,63

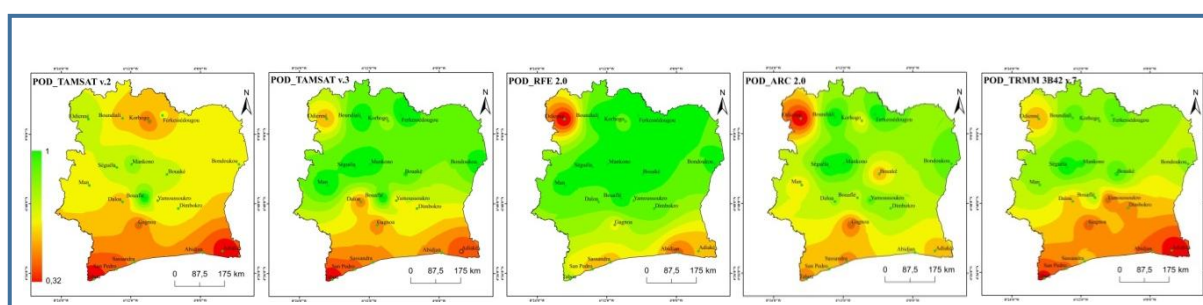
Evaluation of five Satellite Based Precipitation Products over Côte d'Ivoire from 2001 to 2018

	TRMM 3B42 v.7	0,81	0,26	1,11	0,57	0,58	0,40
<b>Daloa</b>	TAMSAT v.2	0,62	0,35	0,96	0,41	0,40	0,26
	TAMSAT v.3	0,58	0,36	0,91	0,45	0,45	0,23
	RFE 2.0	0,91	0,21	1,16	0,73	0,75	0,60
	ARC 2.0	0,91	0,12	1,04	0,81	0,83	0,70
	TRMM 3B42 v.7	0,62	0,31	0,91	0,44	0,43	0,28
<b>Bouaflé</b>	TAMSAT v.2	1	0,60	2,50	0,44	0,70	0,28
	TAMSAT v.3	1	0,60	2,50	0,44	0,70	0,28
	RFE 2.0	1	0,63	2,70	0,40	0,66	0,25
	ARC 2.0	0,90	0,50	1,80	0,54	0,72	0,40
	TRMM 3B42 v.7	0,80	0,63	2,20	0,35	0,52	0,21
<b>Yamoussoukro</b>	TAMSAT v.2	0,70	0,26	0,95	0,54	0,54	0,41
	TAMSAT v.3	0,70	0,30	1	0,55	0,55	0,38
	RFE 2.0	0,95	0,20	1,20	0,78	0,83	0,65
	ARC 2.0	0,95	0,13	1,10	0,85	0,87	0,74
	TRMM 3B42 v.7	0,50	0,28	0,70	0,43	0,40	0,28
<b>Dimbokro</b>	TAMSAT v.2	0,71	0,50	1,42	0,43	0,50	0,28
	TAMSAT v.3	0,73	0,47	1,40	0,45	0,51	0,29
	RFE 2.0	0,93	0,43	1,5	0,61	0,74	0,44
	ARC 2.0	0,93	0,27	1,28	0,75	0,82	0,60
	TRMM 3B42 v.7	0,57	0,55	1,28	0,40	0,44	0,19
<b>Gagnoa</b>	TAMSAT v.2	0,54	0,17	0,65	0,46	0,45	0,31
	TAMSAT v.3	0,58	0,30	0,83	0,50	0,48	0,28
	RFE 2.0	0,80	0,19	1	0,66	0,66	0,50
	ARC 2.0	0,77	0,13	0,88	0,73	0,68	0,53
	TRMM 3B42 v.7	0,50	0,23	0,65	0,40	0,38	0,25

**Table 6:** Overall rain-detection capability of each precipitation product from 2001 to 2018 over Abidjan, Adiaké, Tabou, San Pedro and Sassandra weather stations

STATIONS	SATELLITE DATA	INDICATORS					
		POD [-1; 1] 1=bon	FAR 0=bon	FBI [0; +∞ [ 1=bon	HSS ]-∞; 1] 1=bon	HKSS [-1; 1] 1=bon	ETS [- $\frac{1}{3}$ ; 1] >0 (bon)
<b>Abidjan</b>	TAMSAT v.2	0,55	0,20	0,69	0,43	0,43	0,28
	TAMSAT v.3	0,56	0,22	0,73	0,40	0,40	0,25
	RFE 2.0	0,66	0,26	0,93	0,54	0,54	0,37
	ARC 2.0	0,85	0,22	0,95	0,64	0,64	0,47
	TRMM 3B42 v.7	0,50	0,34	0,76	0,24	0,24	0,14
<b>Adiaké</b>	TAMSAT v.2	0,43	0,05	0,46	0,32	0,38	0,17
	TAMSAT v.3	0,49	0,04	0,51	0,35	0,43	0,20
	RFE 2.0	0,72	0,09	0,79	0,50	0,57	0,32
	ARC 2.0	0,83	0,03	0,85	0,72	0,77	0,57
	TRMM 3B42 v.7	0,39	0,16	0,46	0,19	0,24	0,10
<b>Tabou</b>	TAMSAT v.2	0,43	0,16	0,52	0,11	0,17	0,06
	TAMSAT v.3	0,43	0,16	0,52	0,11	0,17	0,06
	RFE 2.0	0,82	0	0,82	0,70	0,82	0,54
	ARC 2.0	0,80	0	0,80	0,67	0,80	0,50
	TRMM 3B42 v.7	0,43	0,16	0,52	0,11	0,17	0,06
<b>San Pedro</b>	TAMSAT v.2	0,51	0,07	0,55	0,24	0,37	0,13
	TAMSAT v.3	0,53	0,07	0,57	0,16	0,24	0,15
	RFE 2.0	0,74	0,05	0,79	0,48	0,35	0,32
	ARC 2.0	0,83	0,05	0,87	0,56	0,69	0,42
	TRMM 3B42 v.7	0,51	0,04	0,53	0,28	0,44	0,16
<b>Sassandra</b>	TAMSAT v.2	0,57	0,07	0,62	0,30	0,43	0,17
	TAMSAT v.3	0,59	0,06	0,64	0,32	0,45	0,19
	RFE 2.0	0,74	0,05	0,79	0,51	0,60	0,31
	ARC 2.0	0,80	0,05	0,85	0,56	0,66	0,39
	TRMM 3B42 v.7	0,62	0,03	0,64	0,38	0,54	0,23





**Fig. 2:**Probability of Detection (POD) of daily precipitation between rain gauges and TAMSAT v.2 (a), TAMSAT v.3 (b), RFE 2.0 (c), ARC 2.0 (d) et TRMM 3B42 v.7 (e)

### 3.2.Evaluation of meanmonthlyprecipitation

The quantitative statistical indicators of the monthly estimates are presented in Tables 7, 8 and 9. The quality of the correlations as well as the other criteria such as the Nash–Sutcliffe efficiency (NSE) or the RMSE improves as the time step considered is large. The results still significant on a monthly scale.

The correlation between the satellite based products and the ground data is good for all the satellite products ( $R \geq 0.50$  going up to 0.97 for ARC 2.0), except at Bouaflé weather station where RFE is equal to 0.48. The two versions of TAMSAT record coefficients from 0.68 to 0.88 on all the rainfall stations used. The TRMM 3B42 v.7 product is more efficient in Dimbokro, Yamoussoukro and Boundiali and it presents the same performances as RFE 2.0 and ARC 2.0 at the stations of Tabou, Adiaké, Abidjan and Bouaflé. ARC 2.0 and RFE 2.0 have the most constant coefficients on the whole territory. All products have good scores.

The satellite data have a relative distance substantially equal to the reference data, with the exception of TAMSAT v.2 and TRMM 3B42 v.7 which sometimes have NSEs less than 0 at the weather stations of Man, Mankono, Boundiali, Bouaké, Bouaflé, Abidjan, Tabou, San Pedro and Sassandra. ARC 2.0 and RFE 2.0 have the highest and constant NSEs.

RMSEs remain relatively low for all satellite products. This translates into good performance for all products, but, the error is much greater at the weather station of Tabou, Abidjan and Sassandra where there are very high RMSEs for TAMSAT v.2, TAMSAT v.3, RFE 2.0 and TRMM 3B42 v.7.

All products are of very good quality with a monthly time step, ARC 2.0 and RFE 2.0 show the best performance. It can therefore be assumed that the lack of satellite detection is compensated for by greater precipitation accumulations. In summary, satellite products showed diverse performance depending on several factors. Satellite products using a combination of Thermal InfraRed, Passive Microwaves, and GPCC data as input demonstrated better performance than those using fewer sources. Moreover, the good performance of some satellite products may be due to their smaller grid size as it reduces the effect of pixel-to-point comparison [40]. However, the best product depends on the specific application, and time step is of great importance in evaluating the quality of satellite products.

**Table 7:** Monthly statistical indicators from 2001 to 2018 at Ferkessédougou, Korhogo, Boundiali, Mankono, Séguéla and Odienné weather stations

STATIONS	SATELLITE DATA	INDICATORS			
		R [0; 1] 1= parfait	R <sup>2</sup> [0; 1] 1= parfait	NSE ]-∞, 1] 1= parfait	RMSE [0; +∞ [ 0= parfait
<b>Mankono</b>	TAMSAT v.2	0,72	0,52	0,43	41,84
	TAMSAT v.3	0,71	0,51	0,18	50,35
	RFE 2.0	0,85	0,72	0,71	29,99
	ARC 2.0	0,88	0,78	0,78	26,25
	TRMM 3B42 v.7	0,74	0,55	0,10	52,66
<b>Korhogo</b>	TAMSAT v.2	0,80	0,64	0,62	48,94
	TAMSAT v.3	0,81	0,66	0,52	55,07
	RFE 2.0	0,85	0,73	0,73	41,50
	ARC 2.0	0,85	0,72	0,71	43,15
	TRMM 3B42 v.7	0,79	0,63	0,50	56,57
<b>Boundiali</b>	TAMSAT v.2	0,86	0,74	0,72	36,04
	TAMSAT v.3	0,87	0,76	0,44	50,72
	RFE 2.0	0,95	0,9	0,90	21,45
	ARC 2.0	0,94	0,89	0,89	22,74
	TRMM 3B42 v.7	0,81	0,65	0,12	63,68

<b>Ferkessédougou</b>	TAMSAT v.2	0,81	0,65	0,60	45,63
	TAMSAT v.3	0,85	0,72	0,57	47,33
	RFE 2.0	0,89	0,79	0,79	32,93
	ARC 2.0	0,94	0,88	0,88	25,25
	TRMM 3B42 v.7	0,79	0,62	0,44	54
<b>Séguéla</b>	TAMSAT v.2	0,76	0,58	0,44	36,58
	TAMSAT v.3	0,75	0,57	0,04	47,90
	RFE 2.0	0,83	0,69	0,60	31
	ARC 2.0	0,96	0,93	0,93	13,17
	TRMM 3B42 v.7	0,72	0,52	-0,66	63,16
<b>Odienné</b>	TAMSAT v.2	0,88	0,78	0,75	35,15
	TAMSAT v.3	0,88	0,78	0,17	64,65
	RFE 2.0	0,94	0,89	0,86	26,37
	ARC 2.0	0,95	0,91	0,89	23,48
	TRMM 3B42 v.7	0,80	0,64	-0,12	75,44

**Table 8:** Monthly statistical indicators from 2001 to 2018 at Man, Bouaké, Bondoukou, Daloa, Bouaflé, Yamoussoukro, Dimbokro and Gagnoa weather stations

STATIONS	SATELLITE DATA	INDICATORS			
		R [0; 1] 1= parfait	R <sup>2</sup> [0; 1] 1= parfait	NSE ]-∞, 1] 1= parfait	RMSE [0; +∞[ 0= parfait
<b>Man</b>	TAMSAT v.2	0,69	0,48	0,42	45,98
	TAMSAT v.3	0,63	0,40	-1,51	95,44
	RFE 2.0	0,87	0,75	0,75	30,31
	ARC 2.0	0,94	0,89	0,89	20,08
	TRMM 3B42 v.7	0,69	0,48	-0,56	75,18
<b>Bouaké</b>	TAMSAT v.2	0,69	0,47	0,22	39,54
	TAMSAT v.3	0,70	0,49	-0,35	52,11
	RFE 2.0	0,90	0,81	0,78	21,05
	ARC 2.0	0,97	0,94	0,93	11,49
	TRMM 3B42 v.7	0,74	0,55	0,02	44,39
<b>Bondoukou</b>	TAMSAT v.2	0,79	0,63	0,61	44,06
	TAMSAT v.3	0,82	0,67	0,66	41,56
	RFE 2.0	0,88	0,78	0,77	33,55
	ARC 2.0	0,84	0,71	0,71	38,21
	TRMM 3B42 v.7	0,87	0,75	0,74	36,04
<b>Daloa</b>	TAMSAT v.2	0,81	0,65	0,57	50,21
	TAMSAT v.3	0,78	0,61	0,60	48,98
	RFE 2.0	0,84	0,71	0,66	45,09
	ARC 2.0	0,81	0,66	0,63	46,92
	TRMM 3B42 v.7	0,86	0,74	0,71	41,67
<b>Bouaflé</b>	TAMSAT v.2	0,74	0,55	0,49	48,12
	TAMSAT v.3	0,72	0,52	0,48	48,33
	RFE 2.0	0,48	0,23	-0,51	82,67
	ARC 2.0	0,79	0,62	0,59	43,02
	TRMM 3B42 v.7	0,79	0,62	0,54	45,52
<b>Yamoussoukro</b>	TAMSAT v.2	0,81	0,66	0,59	45,29
	TAMSAT v.3	0,79	0,63	0,62	43,19
	RFE 2.0	0,80	0,64	0,59	45,08
	ARC 2.0	0,81	0,65	0,58	45,43
	TRMM 3B42 v.7	0,84	0,70	0,70	38,62
<b>Dimbokro</b>	TAMSAT v.2	0,75	0,56	0,50	47,98
	TAMSAT v.3	0,80	0,64	0,59	43,56
	RFE 2.0	0,88	0,78	0,77	32,35
	ARC 2.0	0,87	0,75	0,74	35
	TRMM 3B42 v.7	0,90	0,81	0,78	31,87
<b>Gagnoa</b>	TAMSAT v.2	0,73	0,54	0,29	72,41
	TAMSAT v.3	0,77	0,59	0,58	55,85
	RFE 2.0	0,84	0,71	0,69	48,12

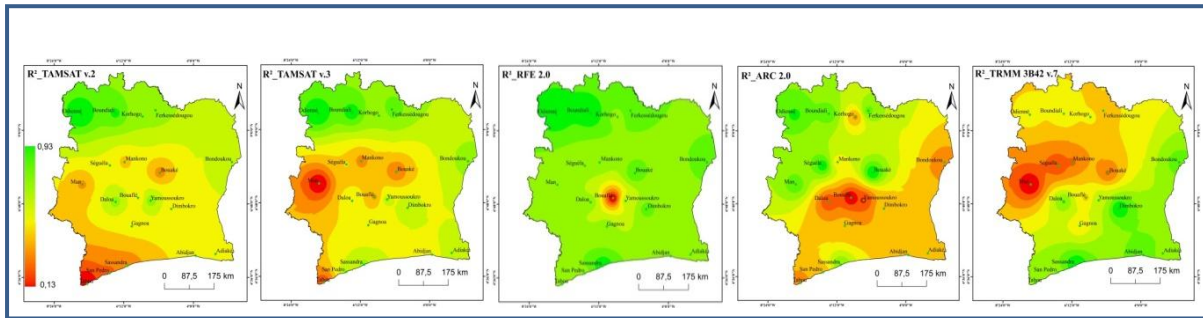
ARC 2.0	0,86	0,74	0,69	47,46
TRMM 3B42 v.7	0,80	0,64	0,61	53,71

**Table 9:** Monthly statistical indicators from 2001 to 2018 at Abidjan, Adiaké, Tabou, San Pedro and Sassandra weather stations

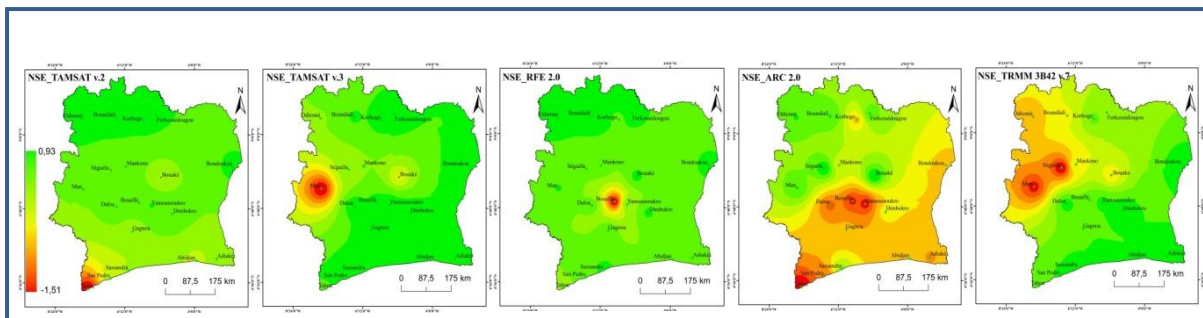
STATIONS	SATELLITE DATA	INDICATORS			
		R [0; 1] 1= parfait	R <sup>2</sup> [0; 1] 1= parfait	NSE ] -∞, 1] 1= parfait	RMSE [0; +∞ [ 0= parfait
<b>Abidjan</b>	TAMSAT v.2	0,75	0,56	0,18	132,34
	TAMSAT v.3	0,77	0,60	0,59	93,48
	RFE 2.0	0,83	0,69	0,59	93,60
	ARC 2.0	0,87	0,76	0,72	76,87
	TRMM 3B42 v.7	0,87	0,76	0,66	84,89
<b>Adiaké</b>	TAMSAT v.2	0,73	0,54	0,29	104,44
	TAMSAT v.3	0,79	0,63	0,62	76,73
	RFE 2.0	0,84	0,70	0,63	75,66
	ARC 2.0	0,85	0,73	0,68	70,61
	TRMM 3B42 v.7	0,85	0,73	0,65	73,47
<b>Tabou</b>	TAMSAT v.2	0,58	0,34	-0,80	176,93
	TAMSAT v.3	0,68	0,46	0,40	131,22
	RFE 2.0	0,84	0,70	0,54	115,85
	ARC 2.0	0,84	0,71	0,56	112,45
	TRMM 3B42 v.7	0,84	0,71	0,46	124,92
<b>San Pedro</b>	TAMSAT v.2	0,66	0,43	0,14	116,27
	TAMSAT v.3	0,79	0,63	0,61	77,81
	RFE 2.0	0,86	0,74	0,64	74,87
	ARC 2.0	0,86	0,74	0,64	74,65
	TRMM 3B42 v.7	0,85	0,73	0,65	74,57
<b>Sassandra</b>	TAMSAT v.2	0,68	0,46	0,25	116,64
	TAMSAT v.3	0,81	0,66	0,66	78,63
	RFE 2.0	0,94	0,88	0,80	59,32
	ARC 2.0	0,93	0,87	0,82	56,15
	TRMM 3B42 v.7	0,90	0,81	0,74	68,06

### 3.3. Spatial and temporal variability assessment

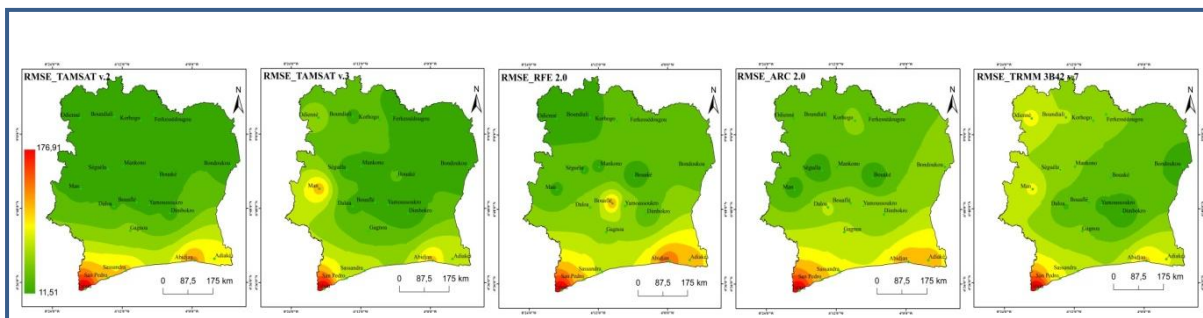
The spatial distribution of the coefficients of determination ( $R^2$ ), Nash–Sutcliffe efficiency (NSE) indices and the Root Mean Square Error (RMSE) of the five products used over the period from 2001 to 2018 are presented in Figs 3, 4 and 5 respectively. TAMSAT v.2, TAMSAT v.3 and ARC 2.0 satellite data show a good correlation with the reference data for the North zone, unlike TRMM 3B42 v.7 which presents this performance in Southern and Eastern (Fig. 3). RFE 2.0 has high correlation coefficients throughout the Ivorian territory except in the Bouaflé area. The differences in performance between the different products is however lower for the inland stations with a smaller range on  $R^2$  and most of the categorical validation statistics. [26] also compared estimations of inland rainfall to coastal rainfall and differences between the satellite products were found to be lower at larger distances from the coast. The analysis of Fig. 4 shows that the entire territory has satisfactory NSE except in Southern zone for TAMSAT v.2, TAMSAT v.2 and RFE 2.0. The ARC 2.0 product presents the distribution of high scores of NSE in the Western, Northern-West and North Central. TRMM 3B42 v.7 records lower values than in the Western. The RMSE mapping generally shows that the Northern and Center areas of the study area record the best values (Fig. 5). The highest RMSE values are observed in the South for all products (Figs 5b and 5e).



**Fig.3** :Spatial distribution of coefficients of determination ( $R^2$ ) between differents satellite-based products and rain gauge of eighteen years monthly mean precipitation over Côte d'Ivoire :TAMSAT v.2 (a), TAMSAT v.3 (b), RFE 2.0 (c), ARC 2.0 (d) et TRMM 3B42 v.7 (e)



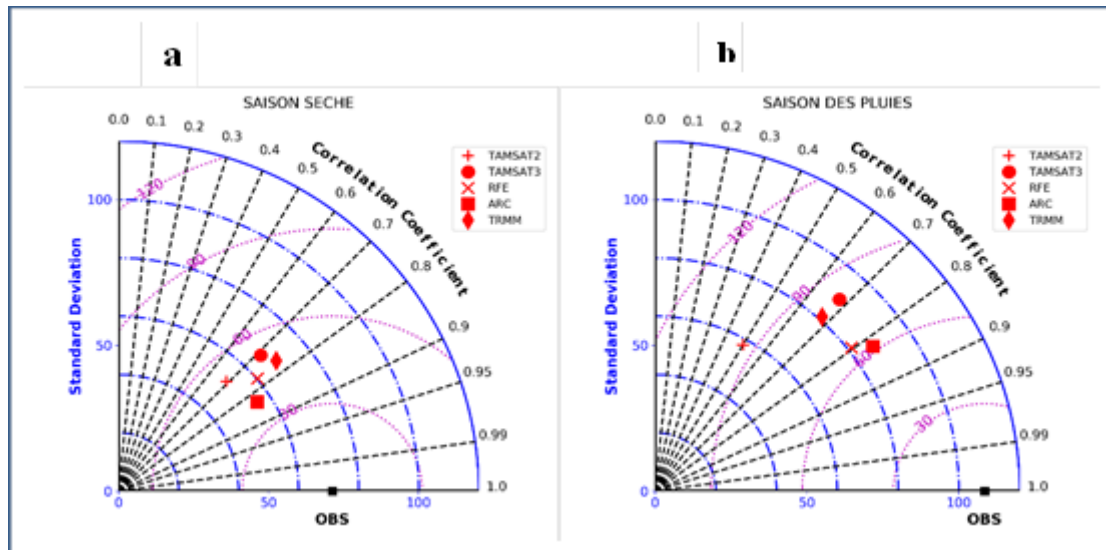
**Fig. 4** :Spatial distribution of Nash–Sutcliffe efficiency (NSE) between differents satellite-based products and rain gauge of eighteen years monthly mean precipitation over Côte d'Ivoire: TAMSAT v.2 (a), TAMSAT v.3 (b), RFE 2.0 (c), ARC 2.0 (d) et TRMM 3B42 v.7 (e)



**Fig. 5** : Spatial distribution of RMSE between differents satellite-based products and rain gauge of eighteen years monthly mean precipitation over Côte d'Ivoire: TAMSAT v.2 (a), TAMSAT v.3 (b), RFE 2.0 (c), ARC 2.0 (d) et TRMM 3B42 v.7 (e)

### 3.4. Comparaison statistique des précipitations saisonnières

Fig. 6 shows the Taylor plots with seasonal precipitation for all the studied weather stations. The two seasons as a whole record a high value of Pearson correlation coefficient ( $R \geq 0.50$  going up to more than 0.80 for ARC 2.0) in the dry season than in the rainy season except TAMSAT v.2. This performance of the data in the dry season could be explained by the difficulty of the products in detecting high intensity precipitation by satellite. RMSEs and standard deviations are generally lower in the dry season. The TAMST v.2 product records the highest RMSE, translating that it performs less than the other products. The most likely reason for this is the poor capacity of the TIR sensor to estimate the actual rainfall amount since the sensor signal does not penetrate the clouds. The algorithms are more efficient in the dry season where ARC 2.0 and RFE 2.0 show the best performance.



**Fig. 6 :** Comparison of dry season (a) and rainy season (b) precipitation statistics (standard deviation, Pearson correlation coefficient, and rootmean square error) of ENSEMBLES data each other with ground observation over all the entire stations combined in a single one from 2001 to 2018.

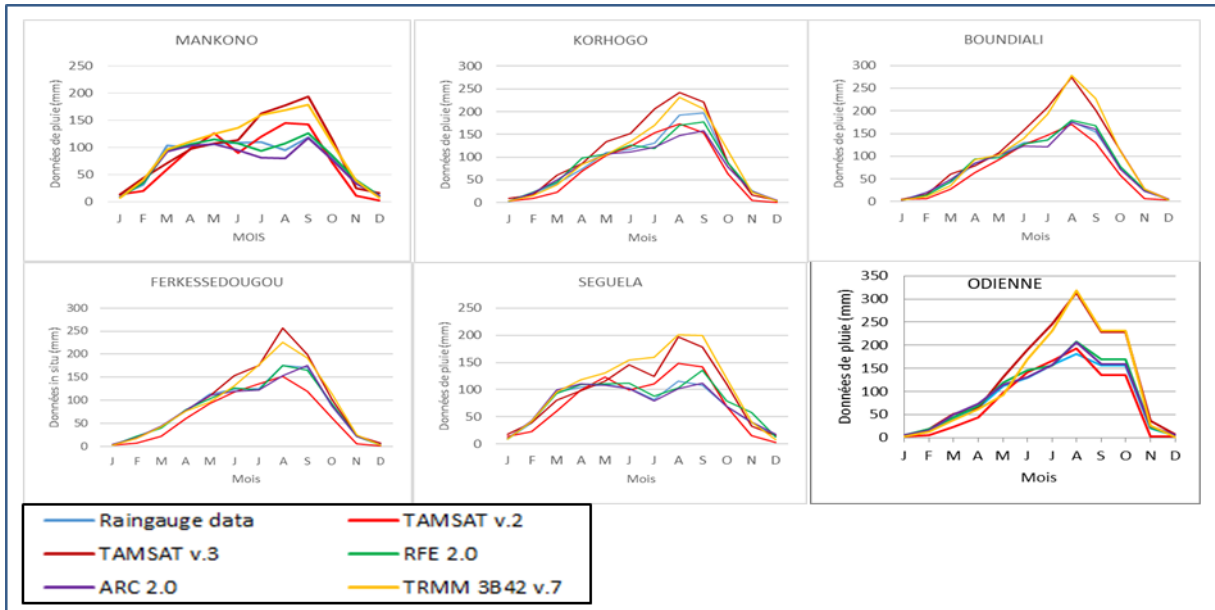
### 3.5. Annual variability of rainfall

Côte d'Ivoire is a country where socio-economic activities are mainly based on rain-fed agriculture. Climate variability, in particular the seasonal evolution of rains, is of primary interest. The climatic variability, in particular the seasonal evolution of the rains, is of primary interest. Figs 7, 8 and 9 show the time series of the annual precipitation cycle at all the stations used over the period 2001-2018.

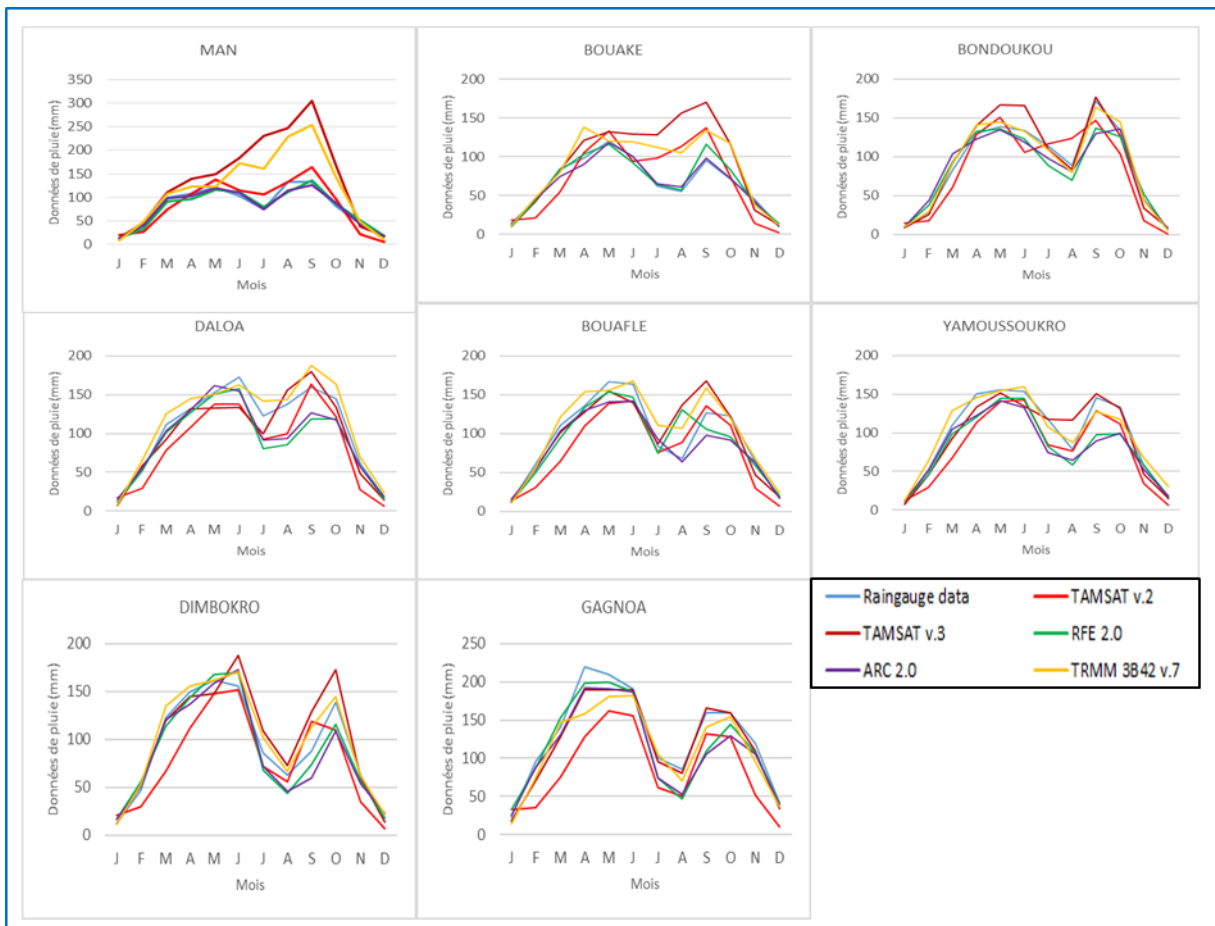
The season May-June is the period when the intensification of the first and the main rainy season occurs in southern of the study area and is followed by a shift towards the northern. A small dry season also occurs in the southern part in July-August, which corresponds to the intensification of the monsoon in northern. September-October corresponds to rainy period in southern. It is then the second and short rainy season in southern of the country [41, 21, 42]. Consequently, a good performance of a satellite product at any of these seasons can be very important in the seasonal climate forecast in Côte d'Ivoire because precipitation is one of the most important indicators of the monsoon variability [41, 42].

In Mankono, Korhogo, Boundiali, Ferkessédougou, Séguéla and Odienné all the products reproduced the unimodal structure of the seasonal cycle. TAMSAT v.3 and TRMM 3B42 v.7 show a wet bias at the peak of the rainy season in August. In Mankono and Boundiali, ARC 2.0, RFE 2.0 and TAMSAT v.2 reproduce the peak of the rainy season. At Ferkessédougou weather station, only ARC 2.0 gives the same maximum in August as the reference data, unlike the RFE 2.0 product which reproduces the same peak, but, in September. At the Center and Southern zones, the bimodal nature of the rainy season is clearly shown by all the models, even if they do not exactly reproduce the magnitude. The quality of the different products varies from weather station to weather station and from season to season. In Man and Bouaké, RFE 2.0 and ARC 2.0 reproduce the variations in the two peaks. In Bondoukou and Yamoussoukro, TAMSAT v.3 and TRMM 3B42 v.7, ARC 2.0 and RFE 2.0 show the closest variations with ground observations. In the Southern zone, in Abidjan, Sassandra and San Pedro alone TAMSAT v.3 gives perfectly the variations in the two peaks. The distribution of monthly rainfall amounts gives a main maximum in June and a secondary maximum in October for the stations in Southern and Center zones. The main minimum is observed in January while the secondary minimum appears between August and September for all averages. The rains are less intense in northern zone with a peak in the month of August. Fig. 10 shows the mean (2001–2018) total annual rainfall for Reference data, TAMSAT v.2, TAMSAT v.3, RFE 2.0, ARC 2.0 and TRMM 3B42 v.7 products. The general north–south gradient of rainfall was captured by all of the analysed products. Reference data, TAMSAT v.3 and ARC 2.0 showed similar spatial patterns, but with slightly less difference in rainfall intensity. RFE 2.0 spatial distribution was close to those of ARC and TAMSAT v.3, except that it seemed to overestimate less rainfall intensities detected by those products. TAMSAT v.2 was close to TRMM 3B42 v.7. TAMSAT v.2 and TRMM 3B42 v.7 had higher estimates for annual total rainfall. They overestimate less rainfall intensities and underestimate high rainfall intensities.



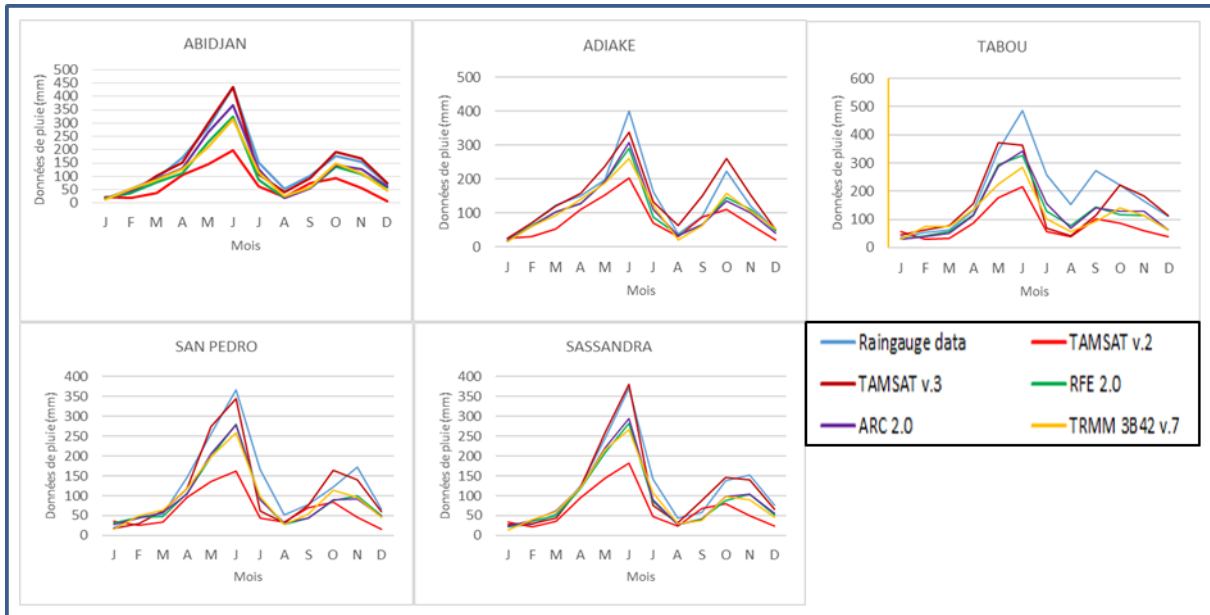


**Fig.7:** Annual cycle of rainfall computed at Mankono, Korhogo, Boundiali, Ferkessedougou, Séguéla and Odiénne over 2001-2018

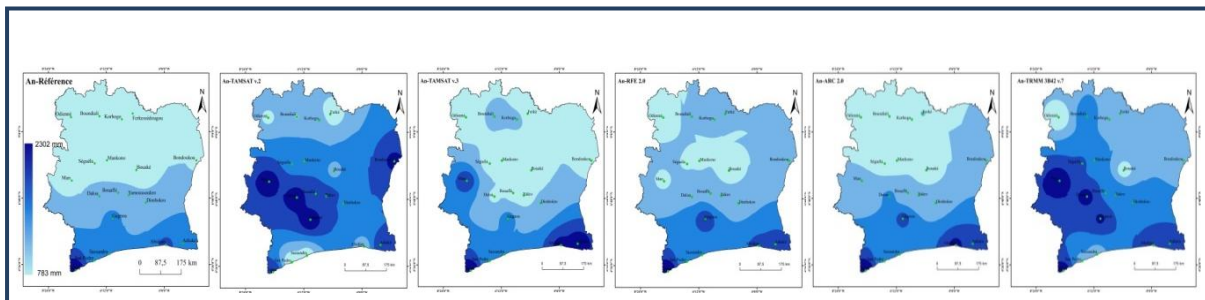


**Fig. 8:** Annual cycle of rainfall computed at Man, Bouaké, Daloa, Bouaflé, Yamoussoukro, Dimbokro and Gagnoa over the period 2001-2018.





**Fig.9:**Annual cycle of rainfall computed at Abidjan, Adiaké, Tabou, San Pedro, Sassandra over the period 2001-2018



**Fig.10:**Mean (2001–2018) total annual rainfall for the different rainfall products: Raingauge data (a), TAMSAT v.2 (b), TAMSAT v.3 (c), RFE 2.0 (d), ARC 2.0 (e) et TRMM 3B42 v.7 (f)

### 3.6. Discussion

Spatial observation is an important instrument for monitoring spatial and temporal variations in rainfall in Côte d'Ivoire, which has a sparse and sparse network of rain gauges. The contribution of data from remote sensing is analyzed through statistical validation. The statistical validation methodology made it possible to make a comparison at four different scales: daily, monthly, seasonal and annual time. Five data were invested for this thesis, TAMSAT v.2, TAMSAT v.3, RFE 2.0, ARC 2.0 and TRMM 3B42 v.7. Several key points of the statistical results can be highlighted. In general, the errors of satellite products are quite large on a daily scale except RFE 2.0 and ARC 2.0 (the best performing). Previous studies [36, 37] note that TRMM 3B42 was better at reporting the occurrence of rainfall than the amounts. Most of the MW techniques rely indeed on high frequencies ( $\geq 85$  GHz), which are more adapted to ice particle detection than to liquid water over a land area, thus explaining why MW satellites miss most of the warm and light precipitation events. Moreover, [43] showed that PMW-based estimates of instantaneous precipitation are more accurate than IR-based algorithms because of the strong relationship between microwave radiance and precipitation. However, the underestimation of heavy rainfall may be caused by the low sampling frequency and consequently missed short-duration precipitation events between satellite measurements [44]. In areas with less surface water, products properly detect rainy days, but poorly detect dry days [39]. [27] indicate that both versions of the TAMSAT daily estimates reliably detects rainy days, but have less skill in capturing rainfall amount - results that are comparable to the other datasets. The recent development of TAMSAT version 3.0 pentadal estimates and derived daily estimates removes spatial artefacts and greatly reduces the dry bias associated with the previous version [27]. The TAMSAT data have most skill when spatially aggregated [27]. However, as time steps are increased, performance improves with all products. And, we can therefore say that the sampling by satellite estimation products is correct with a better and constant performance for ARC 2.0 throughout the study area. The frequencies of biases, the probabilities of detection and the false alarms describe a fairly good quality of the products to detect rainy events. As alternative

sources of precipitation information, future developments of satellite precipitation algorithms and utilization of satellite datasets in operational applications rely on a more in-depth understanding of satellite errors and biases across different spatial and temporal scales. The large bias of certain products may be caused by the failure of these products to differentiate the irradiance properties of the ocean from those of the continent [45]. In particular, the complex processes associated with coastal rainfall are poorly captured [46, 47]. [48] identified systematic anomalies of rainfall retrieval over inland pixels containing small water bodies, such as rivers, lakes and reservoirs. These anomalies are caused by the poor characterization of the differences in emissivity and temperature of water surfaces in the PMW frequencies used by the retrievals. The PMW retrievals are known to be sensitive to land surface heterogeneity, including contrasts in temperature and emissivity [48]. [49] showed that current satellite-based products are more reliable over areas with strong convective precipitation and flat surfaces, as is the case in our study area. Nevertheless, the differences between satellite products and local measurements are largely due to the inability of satellite products to accurately estimate precipitation over coastlines and inland water bodies.

#### **IV. CONCLUSION**

The evolution and availability of continental and global satellite precipitation products with high spatial and temporal resolution increasingly facilitate and stimulate the implementation of climate early warning activities in regions where data are scarce. However, the accuracy, strengths and weaknesses of these satellite products must be assessed before being used for any specific application. A quantification of the uncertainty of these satellite estimates is very useful to users of these data, including hydrologists.

This thesis focused on the lack of rain gauge data in Africa, in particular Côte d'Ivoire, and the possibility of integrating satellite rain data into national databases. It addresses the evaluation of the performance of satellite rain estimates from a set of five data (TAMSAT v.2 and TAMSAT v.3, RFE 2.0, ARC 2.0 and TRMM 3B42 v.7) so that the most appropriate be identified for the study of the climate and proposed to political decision-makers in Western Africa and in particular in Côte d'Ivoire. To achieve this objective, the ground reference data are used for the daily, monthly, seasonal and annual validation of these satellite rain products over the period 2001-2018. Statistical analyses indicate a less performance of TAMSAT v.2, TAMSAT v.3 and TRMM 3B42 v.7 satellite data on a daily scale and this performance varies from one weather station to another and from one climate zone to another over the entire studied period. The products showed an underestimation of the amounts of precipitation in Southern zone and an overestimation of the rains in Northern and Center zones, with a weak correlation with the reference data. However, their performance is becoming more and more precise with the increase in the scale of analysis. ARC 2.0 (more efficient) and RFE 2.0 data are the most efficient at all times and over the entire extent of Côte d'Ivoire. The seasonal and annual ensemble averages show the results closest to ground observations. This could be explained that the use of the overall average exceeds the performance of the individual models. Thus, it illustrates the advantage of multi-model evaluation as mentioned in previous studies [50, 51, 52, 53, 54, 42]. In regions where few gauging stations are available through the online database, satellite estimates constitute a valuable source of meteorological information, but need area-specific calibration and validation [39]. [39] found a greater difference between in situ and satellite estimates in coastal areas against inland areas, probably due to the nature of convective rainfall that is fast, intense and localized [39].

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#### **Author Contributions**

Kouamé Fulgence KOUAMÉ designed the research, performed the analysis, and drafted the manuscript. Koffi Fernad KOUAMÉ (put forward the initial concept), Kouakou Bernard DJE and Kouakou KOUADIO provided specific detail on the ground-based observations and technical expertise on the satellite rain data. All authors commented the manuscript and contributed to the discussion and conclusions.

#### **Conflicts of Interest**

The authors declare no conflict of interest.

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