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Extreme Precipitation Estimates from TRMM in CabindaProvince. Angola

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Abstract: In situ ground observation measurement of precipitation is difficult in vast and sparsely populated areas, with poorroad networks. The use of remote sensors installed in satellites can be useful to overcome this challenge and to improve the description of precipitation spatial variability. This paper examines the accuracy of TRMM 3B42 annual maximum daily precipitation estimates in Cabinda Province,a regionwhere ground monitoring networks are generally inadequate and where studies that evaluate the accuracy of remote sensing estimates are scarce. TRMM 3B42 estimates of annual maximum daily precipitation are compared toground observation data fromthree locations. As a direct comparison between the two datasets for a common specific period and sites is not possible, a statistical approach was adopted to test the hypothesis that the TRMM 3B42 estimates and the ground monitoring records exhibit similar statistical characteristics.

The study shows that the annual maximumdaily precipitation estimates obtained from TRMM 3B42 slightly underestimate the quantiles obtained from the in situ observations. The use of remote sensing products to estimate extreme precipitation values for engineering design purposes is however promising. The paper also presents Intensity Duration Frequency Curves established for return periods of 5, 10 and 20 years. In the future, as the length of the remote sensing data series increases, it may be possible to estimate annual maximum daily precipitation estimates exclusively from these datasets for larger return periods.

Keywords: Maximum daily precipitation, precipitation frequency analysis, intensity duration frequency curves, TRMM, Cabinda.

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I. INTRODUCTION

When drainage conditions are inadequate, extreme precipitation events lead to flooding,to property damage and topotential loss of animal and human life. This risk is particularly severe in developing countries where drainage infrastructure, flood forecasts and emergency management systems are often missing.

Given the significant spatial and temporal variability of precipitation, a large dataset is required to estimate the values associated with extreme events. Traditionally, these data are provided by networks of*in situ* monitoring stations which are costly to maintain in vast and deserted areas, as is the case of many African countries. In Angola, this problemwas further aggravated by the civil war which barred travelling within the country and prevented proper maintenance of most monitoring stations.

Today, there are a number of standard products that mix measurements from sensors installed in satellites with ground observations to offer precipitation estimates on a regular basis, such as TRMM (Huffman *et al*., 1995, Huffman *et al*., 2007), GPCP(Schneider *et al*., 2010), CMORPH (Joyce *et al*., 2004) and PERSIANN (Sorooshian *et al*., 2000). The estimation errors associated with these satellite-derived products arise from many different sources and remain significant, hindering the possibility to recommend a single product to be used in all circumstances. In particular, the reduced number of ground monitoring stations available in Africa to correct, within the algorithm,the original precipitation estimates from remote sensors reduces the accuracy of the final estimates in this continent.

Several studies have evaluated the performance of these remote sensing products to estimate precipitation in Africa by comparing monthly and annual precipitation estimates from remote sensors with ground gauge data (Hughes, 2006; Nicholson *et al*., 2003; Pombo *et al*., 2015), showing that, among the existing products, the precipitation estimates from the TRMMproducts(in particular, the TRMM 3B43 product that offers monthly precipitation values) perform better. Awadallah *et al*. (2011) evaluated the performance of the TRMM 3B42product, which offers precipitation values at 3 hour intervals, in estimatingmaximum precipitation values at six locations in northwest of Angola and concluded that thedata from 3 hours to 24 hours are consistent with the Bell ratios (Bell, 1969).

This paper reviews the estimates of annual maximum of daily values from the TRMM 3B42 product for the CabindaProvince and compares them with values derived from ground measurements. The analysis is based on daily precipitation values because the shortest period of *in situ*precipitation measurementsis daily. Ratios between sub-daily precipitation values and daily precipitation values and intensity duration frequency curves are presented.

The dataset of precipitation ground observations was collected from different sources. This constitutes an important contribution to this scientific and engineering field as the precipitation monitoring data from Cabinda is scarce in international databases.

II. STUDY AREA

Cabinda Province with an area of 7 270 km^2, is a coastal area located in central Africa, south of equator and slightly north of the Congo River, between latitude 4°22'30" and 5°48' south and longitude 12° and 13°13' east. It is one of the 18 provinces of Angola, bordered to the north by the Republic of Congo, to the east and south by the Democratic Republic of Congo (Zaire) and to the west by the Atlantic Ocean. The capital of the province of Cabinda is the city of Cabinda, also known by the name of Tchiowa. There are four municipalities in the province of Cabinda (Cabinda, Cacongo, Buco-Zau and Belize). The Democratic Republic of Congo territory along the north bank of the Congo River separates Cabinda from the Angolan mainland (Figure 1).

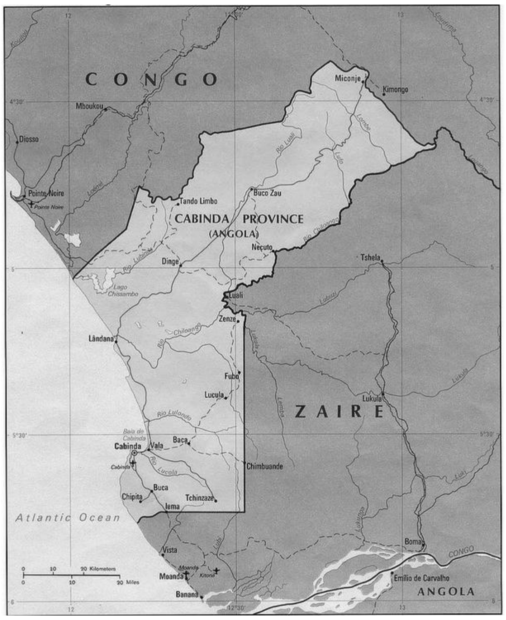

Figure 1 - Cabinda Province location

The greater part of the territory is a low plateau which, in general, terminates along the west in a series of cliffs of no great height. The altitude varies between 0 m and, approximately, 700 m.

Cabinda Province lies on the outskirts of the equatorial climate zone and are considered two types of climate:

- savanna climate covering the low coastal area;
- humid tropical climate covering the NE area of the province.

In Cabinda Province there are two distinctive seasons throughout the year:the rainy season, which lasts approximately six months between November and April, on the coast, and with a duration of about seven months inside, from mid-October to mid-May;the dry season which occurs during the remaining months of the year.

The values of the amount of rainfall increases from the coast to the inland of the province, with the increase in altitude. Thus, in the city of Cabinda (coast), where the altitude is around 20 m, the average annual rainfall is 791.3 mm, while on the inland, in Buco-Zau, with altitudes of 350 meters, the average annual rainfall is 1 258.1 mm. In Belize the average annual rainfall reaches 1 580.5 mm. With regard to temperature, the average annual temperature varies between 25 and 30 °C. The amplitude of the annual average temperature is below 10 °C. In March on the coast, or April on the inland, records the highest average temperatures at around 27 °C. It is the dry season, during the months of July and August, which records the lowest temperatures at around 21 °C.

III. METHODOLOGY

The daily precipitation estimates from TRMM 3B42 (version 7) were evaluated by comparing them with measurements from ground station.

Quality control checks were carried out on the rain gauges records to check if any unknown cause, such as a change in the location of the station or of the measurement equipment and method, might have impaired the series homogeneity and stationarity. Double mass plots and tests on partial means were used to check homogeneity of the annual precipitation data series, and no data series were rejected with a confidence interval of 95%.

When comparing rainfall estimates from satellite products against ground stations measurements the different spatial scales of the two datasets have to be carefully considered. Satellite-based estimates are offered in a grid format, whereas ground measurements comprise precipitation values at specific points. The comparison of precipitation values at a given measurement station requires the computation of satellite estimates at that specific location, which can be obtained by interpolating the values at adjacent cells within the satellite product grid. In this research the inverse-distance-weighting method was applied, whenever interpolation was required. The satellite-based estimates at each station site were computed by interpolating the estimates of the 4 adjacent grid points, assuming that each value refers to the middle point of the grid. Given the dense and regular resolution of the TRMM grid, this method provides an accurate estimate of the TRMM measurement.

The inexistence of a period of concurrent ground measurements and satellite estimates from the different data sources adds another difficulty when comparing the datasets. As a direct comparison between the two datasets for a specific period and site is not possible, a statistical approach was adopted to test the hypothesis that the TRMM 3B42 estimates and the ground monitoring records exhibit similar statistical characteristics (mean and standard deviation).

The definition of daily precipitation in these two data sources is different. For ground measurements it refers to a 24 hours' time window starting between 7:00 and 9:00 am, as the standard practice of the Angola Met Office was to read the rainfall instruments in this morning period. Some errors may arise from this soft definition of daily precipitation, which cannot be eliminated at this point. The satellite estimates uses a fixed time window from 0:00 to 24:00. As in both cases the time window is fixed, a statistical comparison (not a direct comparison) of the data series from both data sources is possible because the consequences of using a distinct definition of daily precipitation should be negligible.

3.1 Homogeneity of the means

The two-Sample t-test for equal means (Snedecor and Cochran, 1989) and the Mann-Withney U test (Stedinger *et al*., 1993) were used to check the homogeneity of the means of the two datasets. The Mann-Withney U test is often viewed as the nonparametric equivalent of Student's t-test. Although it is a non-parametric test it does assume that the two distributions are similar in shape. The test statistic, T, of two-sample t-test for unpaired data is defined as

$$T = \frac{\bar{\mathrm{P}}_{\text{in situ}} - \bar{\mathrm{P}}_{\text{TRMM}}}{\sqrt{\left(\sigma^2/\mathrm{N}\right)_{\text{in situ}} + \left(\sigma^2/\mathrm{N}\right)_{\text{TRMM}}}} \qquad (1)$$

where N is the sample size, $\bar{P}$is the sample mean, and $\sigma^2$is the sample variance. If $|\mathrm{T}| > \mathrm{t}_{1-\alpha/2,\vartheta}$, where $t_{1-\alpha/2,\vartheta}$is the critical value of the t distribution with ϑ degrees of freedom, the null hypothesis that the two means are equal should be rejected.

The Mann-Withney U test compares the differences between two independent (unpaired) groups which are non-normally distributed. The test uses the combined dataset of the datasets under test, ranked in increasing order. The size of the combined dataset is, therefore, $N_{\text{in situ}} + N_{\text{TRMM}}$. If $R_{\text{in situ}}$ is the sum of the ranks of the elements of *in situ* data and R_{TRMM} is the sum of the ranks of the elements of data TRMM both in the combined series, the test statistic, U, of Mann-Withney test is defined as

$$U = \min(\mathrm{U}_{\text{in situ}}, \mathrm{U}_{\text{TRMM}}) \qquad (2)$$

where

$$\mathrm{U}_{\text{in situ}} = \mathrm{N}_{\text{in situ}}\,\mathrm{N}_{\text{TRMM}} + \frac{\mathrm{N}_{\text{in situ}}\,(\mathrm{N}_{\text{in situ}} + 1)}{2} - \mathrm{R}_{\text{in situ}} \qquad (3)$$

and

$$\mathrm{U}_{\text{TRMM}} = N_{\text{in situ}}\,N_{\text{TRMM}} - U_{insitu} \qquad (4)$$

3.2 Homogeneity of the standard deviations

The Levene test based on the median was used to check the homogeneity of the standard deviations (Nordstokke *et al*. 2011). The median based version of the Levene test, an alternative to the original test based on the mean, has been shown to be robust in situations when the dataset presents significant skewness (e.g. Carrol and Schneider, 1985; Nordstokke *et al*., 2011; and Zimmerman, 2004). The Levene test statistic applied to two subgroups of a given variable X (*in situ* and TRMM data) can be defined as

$$W = (N_1 + N_2 - 2) \cdot \frac{\sum_{i=1}^{2} N_i (\overline{Z}_i - \overline{Z})^2}{\sum_{i=1}^{2} \sum_{j=1}^{N_i} (Z_{ij} - \overline{Z}_i)^2} \quad (5)$$

where N_i is the sample size of each subgroup. Z_{ij} is equal to

$$Z_{ij} = \left|X_{ij} - \widetilde{X}_i\right| \quad (6)$$

where $\overline{Z}_i$ are the group means of the Z_{ij} and $\overline{Z}$ is the overall mean of the Z_{ij} and $\widetilde{X}_i$ is the median of each subgroup.

The Levene test rejects the hypothesis $\sigma^2_{insitu} = \sigma^2_{\mathrm{TRMM}}$ if $W > F_{\propto,1,N-2}$, where $F_{\propto,1,N-2}$ is the upper critical value of the F distribution with 1 and N_1+ N_2-2 degrees of freedom at a significance level of α.

3.3 Selection of the probability distribution function

In addition to the statistical tests on the homogeneity of the mean and of the standard deviation of both datasets, the estimates of annual maximum of daily values for different return periods obtained from both datasets were compared. The Gumbel, Pearson III, Galton, log-Pearson type III and GEV distributions were considered. The parameters of the Pearson Type III and log-Pearson type III distributions were estimated using the method of moments, while the linear moment's method was used to estimate the parameters of the Gumbel, GEV and Galton distributions.

The selection of the probability distribution function that best fits the distribution of both the observed data series and the TRMM data series was based on a visual assessment of the probability plot, as well as on the results of the Filiben's test.

The Filiben's test assumes as its *null hypothesis* (H_0) that the dataset follows a given distribution model and that the differences between the observed values, X_i, and corresponding W_i values, estimated by the inverse function of the specific model for empirical probability and plotting positions q_i, are due to sampling fluctuations and are not statistically significant. The statistical test is the correlation coefficient, *r,* between the sorted observations (X_i) and the corresponding data (W_i).

$$W_i = F_X^{-1}(1 - q_i) \quad (7)$$

$$r = \frac{\sum(X_i - \overline{X})(W_i - \overline{W})}{[\sum(X_i - \overline{X})^2 \sum(W_i - \overline{W})^2]^{0.5}} \quad (8)$$

Values of *r* near 1.0 suggest the acceptance of the null hypothesis, while smaller values may lead to its rejection with a pre-specified level of confidence (Chowdhury *et al*., 1991; Stedinger *et al*., 1993; Vogel and McMartin, 1991).

3.4 $\mathbf{P_d^T/P_D^T}$ Ratios

To compute precipitation estimates for durations different than one day, the P_d^T/P_D^Tratios were analysed, where P_d^T is the annual maximum precipitation for a duration d and for a return period of T years and P_D^T is the annual maximum daily precipitation for a return period of T years. The ratios of the average precipitation values were calculated, as well as the ratio of precipitations for the return periods of 5, 10 and 20years.

The TRMM 3B42 records with a time step of 3 hours enables the computation of these ratios for 3 h, 6 h, 12 h, 24 h, 48 h, 72 h, 96 h and 120 h for each cell of the product computational grid. To estimate P_d^T for each location a probability distribution function was adjusted to the time series of annual maximum precipitation in a duration *d*. For the station where the complete daily records is available it was possible to estimate the P_d^T/P_D^T ratios for durations larger than 24 hours, and compare then with the P_d^T/P_D^T ratios obtained from the TRMM 3B42 records.

3.5 Intensity Duration Frequency Curves

The Intensity Duration Frequency Curves are given by the follow equation

$$I = a \cdot t^b \quad (9)$$

where I is the rainfall intensity in mm/h, t is the duration of the precipitation in min and a, b are parameters from de IDF curve.

The most commonly durations used on estimates of extreme rainfall lies between 5 min and 24 hours. Data from 3B42 algorithm have a discretization interval of 3 h, so it is not possible, based on these data, determine the rainfall of less than 180 min. For durations between 5 min and 180 min the equation developed by Bell 1969 (*apud* Shaw, 1984) were used. This equation were obtained based on data from the United States, the ex-URSS, Australia, Puerto Rico, Alaska and South Africa, and the main objective intended to be applied in the estimation of heavy rainfall in countries with scarcity of rainfall data. Equation (10) is representative of one of these relations and is valid to returns period between 2 and 100 years and for durations of precipitation between 5 and 120 min.

$$P_t^T = (0{,}21 \ln T + 0{,}52) \cdot (0{,}54 t^{0{,}25} - 0{,}50) P_{60}^{10} \quad (10)$$

where P_t^T is the precipitation with t duration for the T return period, P_{60}^{10} is the maximum rainfall in 60 min corresponding to a return period of 10 years. The P_{60}^{10} was obtained based on the methodology proposed by Robaina and Peiter 1992. The method proposed by the authors assumed that there is a mathematical expression that defines the relationship between the precipitation at time t and the precipitation in 24h given by the equation (11).

$$P_t^T = P_{24} \cdot F_t \cdot F_T \qquad (11)$$

where P_t^T is the precipitation with t duration for the T return period, P_{24} is the mean annual maximum precipitation with 24h, F_t is a function of aggregation and F_T is a function of the return period. The two functions are given by the follows equations

$$F_t = 7{,}68 \times 10^{-5} + 0{,}1396\ln(1 + 0{,}3333t) \qquad (12)$$

$$F_T = 0{,}4297^m \ T^m \qquad (13)$$

where t is the duration in minutes and the m exponent, function of the t duration, is given by equation (14)

$$m = \frac{0{,}2086\,t}{t+4{,}5969} \qquad (14)$$

IV. DATASETS

4.1 Cabindaprecipitation monitoring network

Precipitation data was collected from distinct sources in Angola and Portugal. Most of the data were collected from printed network record books published by the Angola Met Office and existing at Instituto D. Luiz (Lisbon), the Portuguese National Library and the Angolan National Water Resources Institute. Good practices from the Angola's Met Office stated that an annual maximum daily precipitation value was published only if the complete record of daily precipitation was available for that year.

Table 1 lists the three stations used in the present study and their main characteristics. All stations have more than 20 years of maximum daily precipitation data.

Ground Station	Latitude (°S)	Longitude (°E)	Altitude (m)	Number of Pmax Daily records	Maximum daily precipitation (mm)		
					Mean	Maximum	Minimum
Cabinda	5°33'	12°12'	30	35	83.3	165.3	40.3
Landana	5°13'	12°08'	20	29	93.3	248.4	18.5
Buco-Zau	4°45'	12°32'	350	22	89.0	128.3	56.0

Table 1 - Location and main characteristics of ground stations with more than 20 years of maximum daily. In situ data

For Cabinda ground station where the complete daily records are available,for a period of 23 years, it was possible to estimate theP_d^T/P_D^T ratios for durations larger than 24 h, and compare them with theP_d^T/P_D^Tratios obtained from the TRMM 3B42 records.

4.2 Remote sensing rainfall product - TRMM 3B42

Today, active (i.e. with their own source of electromagnetic radiation as the radar) and passive instruments are used to estimate precipitation from the electromagnetic radiation received from or reflected by clouds and rainfall drops. These remote sensors work in the microwave (MW), infrared (IR) and in the visible bands (VIS). The Tropical Rainfall Measuring Mission (TRMM) was initially a trial mission conceived mainly for the study of tropical and sub-tropical precipitation and to verify its influence on global climate, but it quickly became a reference for the study of precipitation (Kummerow *et al.*, 1998). The instruments aboard the TRMM satellite are the TRMM Microwave Imager (TMI), the Precipitation Radar (PR) and the Visible Infrared Scanner (VIRS), the Cloud System and Earth Radiant Energy Sensor (CERES) and the Imaging Lightning Sensor (LIS). The TRMM products incorporate data from TRMM satellite instruments and measurements made by a variety of other low earth orbit platforms and geostationary satellites to provide precipitation estimates with a spatial resolution of 0.25° lat/long (Huffman *et al.*, 1995; Huffman *et al.*, 2007). External data sources used in the TRMM algorithms include passive MW sensors from the DMSP (Defense Meteorological Satellite Program), the Aqua satellite and the NOAA satellite series, as well as the IR data from international constellation of geosynchronous earth orbiting satellites. To calibrate and improve the reliability of estimates and minimize the differences between satellite estimates and ground measurements, there is a parallel program of ground validation that uses weather radar and rain gauges in various stations along the inter-tropical track. Over West Africa, the TRMM product has good results when compared with gauge data at a monthly time step (Nicholson *et al.*, 2003, Pombo *et al.*, 2015).

The two principal products from this family, 3B42 and 3B43, offer a temporal resolution of three hours and one month, respectively, and a common spatial resolution of 0.25° lat/long, in the range between 50°S and

50°N. The 3-hour interval dataset used in this research was from the TRMM3B42 product (version 7) and runs from October 1998 to September 2013. It was obtained at http://mirador.gsfc.nasa.gov/services.Table 2 lists the main characteristics of maximum daily precipitation estimates from TRMM 3B42 for the location of the three ground stations.

Ground Station	**Mean of maximum daily precipitation (mm)**	**Maximum daily precipitation (mm)**	**Minimum daily precipitation (mm)**
Cabinda	83.9	154.4	55.3
Landana	86.7	224.2	57.2
Buco-Zau	82.7	131.1	52.2

Table 2 - Main characteristics of maximum daily precipitation estimates from TRMM 3B42 for the location of the three ground stations

V. RESULTS

5.1 Homogeneity tests

The results of the tests on the homogeneity of the means of the TRMM and *in situ* datasets, using a significance level of 5%, show that the null hypothesis is not rejected at any location.The results of Levene's test to check the homogeneity of the variance, with a significance level of 5%,show that the null hypothesis is not rejectedonthe stations under scrutiny.

5.2 Comparison of annual maximum daily precipitation estimates

The correlation *r* values of Filiben's test for several probability distribution functions showed that the GEV function is able to describe the distribution of the *in situ* annual maximum daily precipitation values. Adopting a significance level of 5%, the GEV distribution is never rejected for all data series under scrutiny.

5.3 Precipitation estimates for durations longer than one day

The data gathering effort put forward for this research was able to recover the complete records of daily precipitation for Cabindamonitoring station. For this location the annual maximum precipitation values for durationsof48h, 72h, 96h and 120h were obtained from the ground monitoring records and from TRMM 3B42 satellite estimate records. Various probability distribution functions were analysed to describe the annual maximum values for durations of 48h, 72h, 96h and 120h and the GEV function lead to the best adjustments. The GEV distribution was not rejected at any duration. Table 3 shows the annual maximum precipitation values for durations of 48h, 72h, 96h and 120h and for return periods of 5, 10, and 20 years, for both datasets. AccordingTable 3 the annual maximum daily precipitation estimates obtained from TRMM 3B42 slightly underestimate the quantiles obtained from the *in situ* observations. Collischonn *et al.* (2008) had already verified this underestimation tendency when analysing TRMM 3B42 precipitation estimates for Brazil.

Duration	**Return period (*In Situ* / TRMM)**		
	5 years	**10 years**	**20 years**
Daily	103.4 / 100.2	117.3 / 114.6	129.9 / 128.9
48h	122.8 / 111.0	139.7 / 126.8	154.6 / 143.5
72h	130.4 / 119.4	145.7 / 135.3	159.0 / 151.9
96h	139.7 / 132.4	153.8 / 147.0	165.4 / 162.0
120h	154.5 / 135.7	172.1 / 150.4	186.8 /165.2

Table 3 - Annual maximum precipitation values for durations of 48h, 72h, 96h and 120hand for different return periods, for both datasets

Table 4 shows the average ratio$\bar{P}_d/\bar{P}_D$ and the P_d^T/P_D^T ratio of annual maximum precipitation in *d* hours to the annual maximum daily precipitationfor return period T, obtained from the *in situ* and TRMM data, forCabindalocation.The values obtained for the P_d^T/P_D^Tshowthe reduced influence of the return period on these. TRMM 3B42 slightly underestimate this ratios.

Ratios	$\bar{P}_{48}/\bar{P}_D$	$\bar{P}_{72}/\bar{P}_D$	$\bar{P}_{96}/\bar{P}_D$	$\bar{P}_{120}/\bar{P}_D$
In Situ	1.13	1.26	1.36	1.48
TRMM	1.15	1.25	1.44	1.47
Ratios	P^5_{48}/P^5_D	P^5_{72}/P^5_D	P^5_{96}/P^5_D	P^5_{120}/P^5_D
In Situ	1.18	1.25	1.34	1.49
TRMM	1.11	1.19	1.32	1.35
Ratios	P^{10}_{48}/P^{10}_D	P^{10}_{72}/P^{10}_D	P^{10}_{96}/P^{10}_D	P^{10}_{120}/P^{10}_D
In Situ	1.19	1.24	1.31	1.47
TRMM	1.11	1.18	1.28	1.31
Ratios	P^{20}_{48}/P^{20}_D	P^{20}_{72}/P^{20}_D	P^{20}_{96}/P^{20}_D	P^{20}_{120}/P^{20}_D
In Situ	1.19	1.22	1.27	1.45
TRMM	1.12	1.18	1.26	1.28

Table 4 - P_d^T/P_D^T ratios where P_d^T is the precipitation with duration of 48h, 72h, 96h and120h for a return period of T years and $P_D^T$is the annual maximum daily precipitation for a return period of T year both computed from the in situ and TRMM 3B42 precipitation dataset using the GEV distribution

Table 5shows the ratios of$\bar{P}_d/\bar{P}_D$, for the other locations computed from the TRMM 3B42 precipitation, where $\bar{P}_d$ is the precipitation with duration of 48h, 72h, 96h and 120h for the average values for those durations and $\bar{P}_D$ is the annual maximum daily precipitation. Comparison between Table 4 and Table 5 show that the values obtained for the $\bar{P}_d/\bar{P}_D$ ratios of annual maximum precipitation for durations of 48h, 72h, 96h and 120h are quite similar in Cabinda and Landana but in Buco-Zau these are higher. Buco-Zau is located at a higher altitude (350 m) and the values obtained reflect the influence of altitude on rainfall.

Ratios	$\bar{P}_{48}/\bar{P}_D$	$\bar{P}_{72}/\bar{P}_D$	$\bar{P}_{96}/\bar{P}_D$	$\bar{P}_{120}/\bar{P}_D$
Landana	1.16	1.32	1.39	1.47
Buco-Zau	1.21	1.34	1.55	1.71

Table 5 - $\bar{P}_d/\bar{P}_D$ ratios of annual maximum precipitation for durations of 48h, 72h, 96h and 120h obtained from TRMM data at Landana and Buco-Zau

5.4 Sub-daily precipitation estimates

Table 6showstheratios of $\bar{P}_d/\bar{P}_D$,in Cabinda Province computed from the TRMM 3B42 precipitation, where $\bar{P}_d$ is the precipitation with duration of 3h, 6h, 12h and 24hfor theaverage values for those durationsand $\bar{P}_D$ is the annual maximum daily precipitation.

Ratio/Station	**Cabinda**	**Landana**	**Buco-Zau**
$\bar{P}_3/\bar{P}_D$	0.66	0.73	0.68
$\bar{P}_6/\bar{P}_D$	0.85	0.89	0.91
$\bar{P}_{12}/\bar{P}_D$	0.96	1.02	0.99
$\bar{P}_{24}/\bar{P}_D$	1.02	1.07	1.08

Table 6 - $\bar{P}_d/\bar{P}_D$ ratios al maximum precipitation values for durationsof 3h, 6h, 12h and 24h obtained from TRMM data

The ratios for $\bar{P}_{12}/\bar{P}_D$and $\bar{P}_{24}/\bar{P}_D$can begreater than one because $\bar{P}_{12}$ and $\bar{P}_{24}$are computed by selecting in each year the continuous time window of 12h and 24h that maximize the precipitation amount, while $P_D$corresponds to the annual maximum precipitation in a fixed time window. Several authors have highlighted this fact such as WMO (1994) and Jakob *et al*. (2005).

The values estimated in Cabinda Province by the TRMM 3B42 product are closed to previous estimatessuch as Hershfield's (1962) who proposed a value of 1.13 for the relationship $P^T_{24h}/P^T_D$for the EUA and Montfort's (1997) who analysed 130 Chinese stations and obtained values between 1.04 and 1.16 for the P^T_{24h}/P^T_Dratio. Brandão *et al.* (2001)analysed 30 gauges in Portugal and concluded that theP^T_{24h}/P^T_Dratio ranged between 1.028 and 1.373 and was not dependent on the return period, very similar to the interval obtained for Angola, between 1.017 and 1.360.

5.5 Intensity Duration Frequency Curves

Tables 7 to 9 show de Intensity Duration Frequency Curves for the three stations analysed. Figure 2 show the Intensity Duration Frequency Curves for Cabinda and for different return periods.

Duration	Parameters	Return period (years)			
		Average	5	10	20
t ≤ 180 min	a	336.9	414.3	484.6	554.9
	b	-0.568			
180 min < t < 24 h	a	1230	1501	1712	1907
	b	-0.800			
24 h ≤t < 5 days	a	764.5	932.3	1064	1185
	b	-0.746			

Table 7 - Intensity Duration Frequency Curves: Cabinda

Duration	Parameters	Return period (years)			
		Average	5	10	20
t ≤180 min	a	399.7	491.5	574.9	658.3
	b	-0.568			
180 min< t < 24 h	a	1909	2487	2908	3293
	b	-0.843			
24 h ≤t < 5 days	a	1295	1687	1973	2234
	b	-0.792			

Table 8 - Intensity Duration Frequency Curves: Landana

Duration	Parameters	Return period (years)			
		Average	5	10	20
t ≤ 180 min	a	382.4	470.3	550.1	629.9
	b	-0.568			
180 min < t < 24 h	a	1528	1781	1914	2020
	b	-0.819			
24 h ≤t < 5 days	a	744.2	867.3	932.3	983.8
	b	-0.723			

Table 9 - Intensity Duration Frequency Curves: Buco Zau

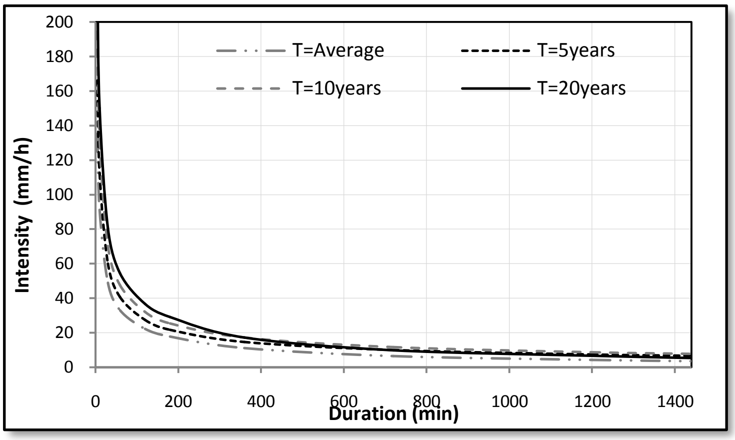

Figure 2 - IDF Curves for Cabinda ground station and different return periods

VI. FINAL COMMENTS

The analysis presented in this paper shows that the TRMM 3B42 algorithm can reproduce reliable estimates of the annual maximum daily precipitation for Cabinda Province.

The 3-hour time interval of the TRMM 3B42 record allowed the computation of the ratiosP_d^T/P_D^T, where P_d^T is the maximum precipitation with duration *d* with a return period of *T* years and P_D^T the maximum daily precipitation with a return period of *T* years. The P_d^T/P_D^T for the return periods of 5, 10 and 20 years suggests the reduced influence of the return period in these ratios.

These are important results to obtain precipitation estimates for durations between 3h and 24h, as sub-daily precipitation records in Cabinda Province. The$\bar{P}_{24}/\bar{P}_D$ratios lies between 1.02 and 1.08and these values compare well with previous results such as Hershfield (1962) for the USA, Montfort (1996) for China and Brandão *et al*. (2001) for Portugal.

Despite the short length of the TRMM record and the existing local disparities between the estimates obtained from the *in situ* historical record and the TRMM 3B42 dataset, the results show that the TRMM records are of great interest in estimating extreme precipitation values associated with different return periods. The Intensity Duration Frequency Curves presented in this paper enable the computation of annual maximum precipitation estimates for specific precipitationdurations and for average values and for different return periods.

For the future, the use of remote sensing products to improve extreme precipitation estimates for engineering design purposes is promising. As the length of the remote sensing data series increases and the rebuild of monitoring network in Cabinda makes possible the comparison of contemporaneous precipitation estimates from *in situ* monitoring stations and TRMM sensors, the TRMM algorithms it may be possible to estimate annual maximum daily precipitation estimates exclusively from these datasets.

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