International Journal of Innovation and Scientific Research
ISSN 2351-8014 Vol. 49 No. 1 Jun. 2020, pp. 75-88

http://www.ijisr.issr-journals.org/

Seasonal variability of raindrop size distributions characteristics regarding to climatic parameters over coastal area of West Africa

Bakary Bamba, Eric-pascal Zahiri, Modeste Kacou, Abé Delfin Ochou, Yves Kouassi Kouadio, Ibrahima Bamba, and Augustin Kadjo Koffi

Laboratoire de Physique de l'Atmosphère et de Mécanique des Fluides, UFR SSMT, Université Félix Houphouët-Boigny, 22 BP 582 Abidjan 22, Côte d'Ivoire

ABSTRACT: A seasonal variability study of tropical raindrop size distributions (DSD) and integrated rain parameters in West Africa coastal area (Abidjan, Côte d'Ivoire) was done. The study covered the period 1986 to 1988 with a focus on 1987 for a complete annual cycle investigation using the EPSAT validation experiment data. The following parameters have been described: the median volume diameter (D_0), the total number of drops per unit volume of air (N_T), the ratio D_0/N_T, the rain rate (R) as well as the radar reflectivity factor (Z). During the May-June (MJ) and September-October-November (SON) seasons, the characteristics of DSD in June 1987 (D_0 strong and N_T low) compared to those of October 1987 (D_0 strong and N_T strong) could explain the high rainfall recorded during SON compared to MJ where the rainfall is lower. The Sea Surface Temperature (SST) analysis of these two seasons indicate a modulation of this inversion by ocean surface conditions. In general, a high SST induces important rain with spectra containing a large number of large drops due to strong convection associated with a large advection flow. Finally, raindrop size distributions appeared to be relevant indicators to characterize the specific behaviour of the rainy seasons.

KEYWORDS: Raindrop size distributions, Sea Surface Temperature, Rainy seasons, Rainfall, Coastal area, Convection, Advection flow.

1 INTRODUCTION

In West Africa region, monsoon is a major phenomenon driving rainy seasons, characterized by strong temporal and spatial variability. In these developing countries of West Africa depending on the monsoon system, agriculture yields and water resources availability are affected by the temporal variability of monsoon. Also, West Africa, located in the northern hemisphere and bordered by the Guinean coast in the south (five degrees north of the equator), during the boreal summer, the African continent warms up rapidly and becomes warmer than the waters of the Gulf of Guinea. This thermal contrast between the two surfaces (Continent and Ocean) with different inertia leads to large-scale atmospheric circulation. A "sea breeze" of regional scale is being formed, leading to the penetration of a cool, moist south-westerly ocean air flow commonly known as monsoon flow on the African continent. The latest, going up towards the Northeast, meets a flow of warm and dry air, coming from the Sahara. Monsoon rains develop on the continent in the interaction zone of these two masses of air [1].

Precipitation in the West African monsoon is highly variable in space and time, regardless of the scales considered, local or regional, diurnal, intra-seasonal, seasonal or inter-annual. Recent studies [2], [3] revealed an intra-seasonal variability of the West African monsoon through the identification of various main modes of variability associated with three types of timescales: about 40-days, 15-days and 3 to 10 days. However, this variability has rarely been related to the microstructure of precipitating systems, including the raindrop size distributions (DSD). Such approach would be useful to elucidate the characteristics of dsds in the West African region, better understand the variability of their relationship with rainfall estimation algorithms and get information concerning the generating processes of the monsoon precipitating systems. Indeed, one of the main causes of rainfall retrieval uncertainty using precipitation radar aboard satellite (e.g. TRMM) is the misapprehension of global DSD characteristics [4], [5]. This is of interest for the exploitation of recent space missions measurements such as Megha-Tropiques [6], Global Precipitation Measurement (GPM) [7].

For the particular case of West Africa, it is well documented from previous studies that the raindrop size distributions vary with respect to time and space due to the complexity of the atmospheric and climatologic system [8], [9], [10], [11], [12], [13], [14], [15]. This variability is certainly related to the nature of the convective systems but also related to the climatic factors that modulate the monsoon flow. However, very few studies have been devoted to establish links between these climatic factors and the characteristics of the DSD. In addition, in the tropics, especially in West Africa, one of the most fundamental climatological characteristic is the Inter-Tropical Convergence Zone (ITCZ), Which is mainly marked by enhanced convective activity, cloudiness and precipitation [16], [17]. The onset stage of the African summer monsoon is linked to an abrupt latitudinal shift of the ITCZ from a quasi-stationary location at 5°N in May–June to a second quasi-stationary location at 10°N in July–August [18]. According to [19], this stage corresponds to major changes in the atmospheric circulation over West Africa linked to the full development of the summer monsoon systems. Thus, sub-seasonal variations of ITCZ position could impact the quantity of total rainfall as well as the intrinsic characteristics of rainy system's microstructure. Also, a better understanding of the ITCZ position, structure, and migration is clearly important for describing the atmospheric processes and types of precipitating systems prevailing in the region as well as the inherent DSD characteristics.

Elsewhere, some studies explained that rainfall variability in West Africa region is partially controlled by Sea Surface Temperature (SST) variations. Many local studies confirmed the key role of the ssts on the rainfall variability in West Africa. Reference [20], as well as [21], showed a possible strong correlation between ssts in the Tropical Atlantic and the rainfall in Ghana and Côte d'Ivoire. The latest [21], based on statistical correlations between oceanic SST and precipitation, showed an impact of the tropical Atlantic SST on the precipitation in Côte d'Ivoire. In addition, recent work from [22] revealed that coastal precipitations of the July-September period are correlated with both the coastal and equatorial SST. This correlation results in a decrease (an increase) of rainfall when the ssts are abnormally cold (warmer). Therefore, SST appears as a key parameter for the modulation of precipitation variability. Nevertheless, in all these studies none reference has been done to the behavior of DSD. However, an analysis of changes in raindrop size distribution characteristics with distinctive time scales, namely inter-annual, seasonal, and intra-seasonal may allow catching process by which they are related to precipitation type [23] and to other climatic parameters such as ITCZ and SST variations.

This paper addresses the imperative interrogation of the DSD characteristics in different seasonal (cold and warm), atmospheric (dry and wet) and pluviometrical regime (abnormal and normal) contexts. The present study includes variations of DSD integrated parameters (e.g. Raindrops concentration N_T, median volume diameter D_0) in relation to rainfall amount, SST, and ITCZ. One of the main objectives of this paper is to understand the variability of dsds in various seasonal and atmospheric perspectives. It will also examine process by which rainy season specificities are reflected in terms of DSD relating to SST.

We structure this paper as follows: Data and methodology used are described in Section 2. Results are presented and discussed in Section 3. At last, in Section 4, we summarize the study and provide the conclusions of this work.

2 MATERIALS AND METHOD

Data used in this study are from J-W impact-type disdrometer located in Abidjan (5.25°N – 4°W), in southern Côte d'Ivoire, along the Guinea Gulf coast for the years 1986 to 1988. Table 1 lists the period of disdrometer data at the observation site. The dataset consists of 24896 continuous one-minute drop size distribution (DSD) samples, corresponding to about 22 months. The spectra are recorded as number of drops in 25 intervals of drop diameters ranging from 0.3 to 5.3 mm, all with the same width of 0.2 mm. Since the disdrometer data are affected by uncertainties due to drop sorting and small sampling volume [24], [25], one-minute DSD with rainfall rate less than 0.05 mmh^{-1} and total number of drops less than 5 are discarded to avoid the under-sampling effect [26].

Table 1. Observation periods at Abidjan and number of DSD in the samples

Year	Period of disdrometer data	Number of DSD in the sample
1986	June; Sept. To Dec.	3008
1987	Jan. To Dec,	16049
1988	Jan. To June	5839

From the information on raindrop size distribution, some integrated rainfall parameters such rain rate (R), the radar reflectivity factor (Z), the total number of drops N_T per unit volume of air, and the median volume diameter (D_0) are estimated and used to describe the DSD characteristics. They are generally calculated by the following theoretical expressions:

$$R = 6\pi 10^{-4} \int_0^{+\infty} D^3 N(D) V(D) dD$$

$$Z = \int_0^{+\infty} D^6 N(D) dD$$

$$= \int_0^{+\infty} N(D) dD$$

$$\frac{W}{2} = \frac{\pi}{6} \rho_w \int_0^{D_0} D^3 N(D) dD$$

Where, the median volume diameter D_0 is defined as the diameter of which the water content W is divided per 2.

Another form of DSD characteristics analysis can be conducted through investigating the Z–R relationship between radar reflectivity and rainfall rate. This relation is mostly used for rainfall estimation from radar measurements and defined by a power law $Z = AR^B$. In the present study, Z-R was estimated from the least square fitting method, which is based on estimating multiplicative factor *A* and exponent *b* by optimizing the differences in logarithm scale.

Reference [27] successfully associates one type (convective/stratiform) and one (isolated/organized) rainfall structure in each of the four (4) seasons considered. One of the challenges is to analyze the seasonal variability of the integrated parameters of dsds. Moreover, based on the fact that SST is a parameter of key climatic interest in modulating the high variability of precipitation in the Gulf of Guinea, it makes sense to analyze its variability in relation to that of the integrated parameters of dsds considered to be the result of the microphysical processes responsible of the formation of precipitation.

Therefore, we investigate the seasonal variability of DSD in relation to climatic parameters (rainfall, SST, and FIT).

3 Results And Discussion

3.1 Observation Site And Rainfall Characteristics

This study is carried out on the site of Abidjan (5 ° 25N - 4 ° W), located in the coastal zone of the Côte d'Ivoire, bordering the Gulf of Guinea (Fig. 1). It is characterized by a bimodal seasonal cycle with a rainfall peaks in June (> 500 mm) and October (~ 120 mm) [27], [21]. Thus, the two modes show as first rainy season the period of May-June and as the second rainy season the period of September-October-November, which will be recorded in the following as MJ and SON respectively. These two rainy seasons are separated by a long dry season, from December to mid-February, marked by the Harmattan, followed by an inter-stormy season, from mid-February to the end of April and finally by a small dry season (July-August).

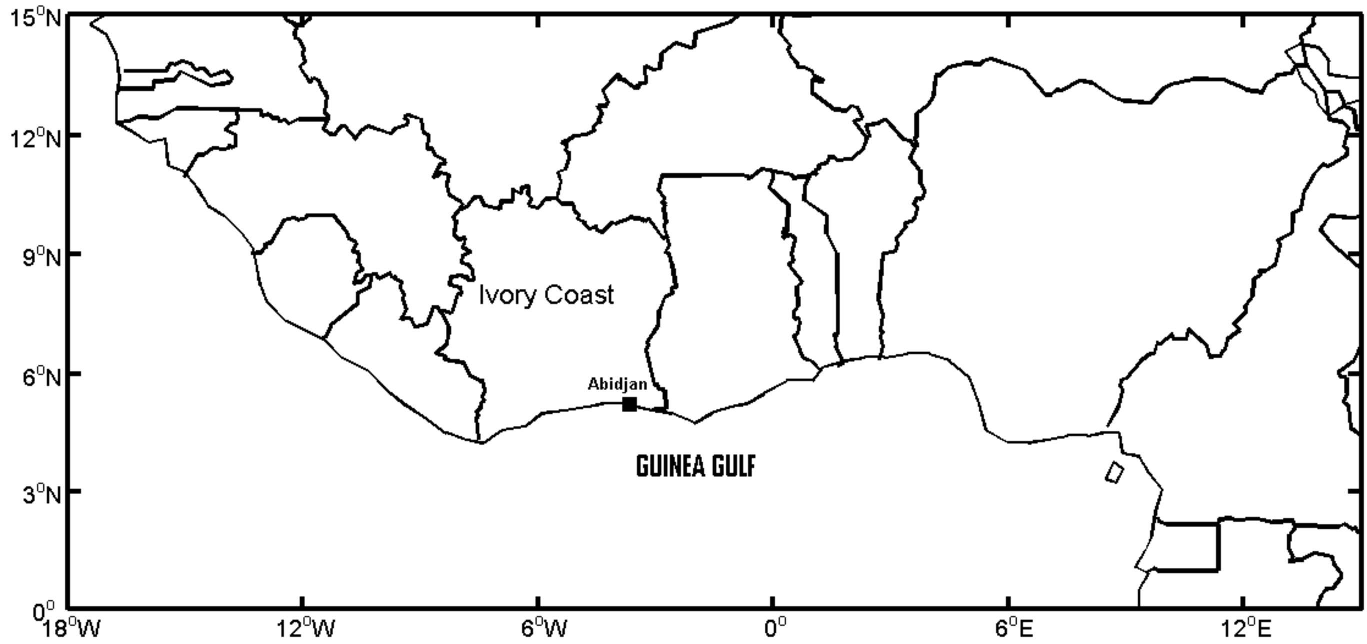

Fig. 1. Observation site indicated by the solid black square in Côte d'Ivoire

Fig. 2a simultaneously presents the isohyets of the years 1986, 1987 and 1988 for comparison. The existence of the aforementioned peaks is noted. However, the analysis of this figure shows that the year 1987 has a very particular seasonal cycle. Although the distribution of rainfall remains bimodal, we note that, contrary to 1986 and 1988, the 1987 rainfall is characterized by a reversal of the modes, reflected by low rainfall in May-June (minor mode) and exceptional rainfall in SON (major mode). Thus, with an exceptional rainfall recorded during the month of August (~ 100 mm), this configuration made 1987 an atypical year. Numerous studies have noted that in the Gulf of Guinea as a whole, in 1987 there was a positive anomaly of rain due to a very abundant small rainy season. This trend is confirmed by the exceptional rainfall observed in all the countries bordering the Gulf of Guinea [28], notably in Benin, where rainfall was recorded between 400 and 500% normal according to the ASECNA Bulletin in 1987 cited by [27]. To examine the factors likely to explain this inversion of the major and minor rainfall patterns during the atypical year 1987, these inversions are compared with oceanic and meteorological parameters. In particular, we are interested in the influence of the tropical Atlantic through SST and pseudo-wind stress as well as the latitudinal position of the ITCZ characterized by its ground trace (FIT). Monthly changes in SST and FIT are shown in Fig. 2b and 2c in conjunction with monthly rainfall amounts (Fig. 2a). The monthly latitudinal evolution of FIT during MJ and SON shows similarities for the three years 1986, 1987 and 1988. This configuration indicates that the meteorological parameter such as FIT cannot justify this inversion of the peaks during MJ and SON. However, the evolution of SST makes it possible to demonstrate a closer link with the variations of precipitations during these two rainy seasons. Firstly, there is an abnormal cooling of surface water not only in Abidjan (Fig. 2b) but along the entire West African coast in MJ 1987 (Fig. 3), combined with a decrease in rainfall in MJ this year 1987 compared to the years 1986 and 1988. Secondly, the study of pseudo- wind stress (Fig. 3) shows a weakening of the wind towards the northern coast of the Gulf of Guinea in MJ. Such a situation could be related to an accumulation of cold water in the Gulf of Guinea and could explain the cooling observed on the West African coast in MJ. According to the work from [29], the cooling observed over the West African coast is opposed to convective movements in the lower troposphere and creates a stabilization of air masses. Thus causing an effect of inhibition of convection in the Gulf of Guinea coastline from April to June. The decline in rainfall over the coast of the Gulf of Guinea in June 1987 would result from this situation. Finally, there is an abnormal warming of the ocean on the West African coast in August, September, October and November (Fig. 2b) causing a high availability of water vapour in the atmosphere. Fig. 3 presents pseudo-wind stress and SST positive anomalies in August 1987. It shows an intensification of the moisture flow likely to trigger strong convective activity during the rainy season SON. According to [29], this configuration induced strong convection and advection of the monsoon flow, probably causing rainfall increasing over the littoral during the small rainy season of 1987.

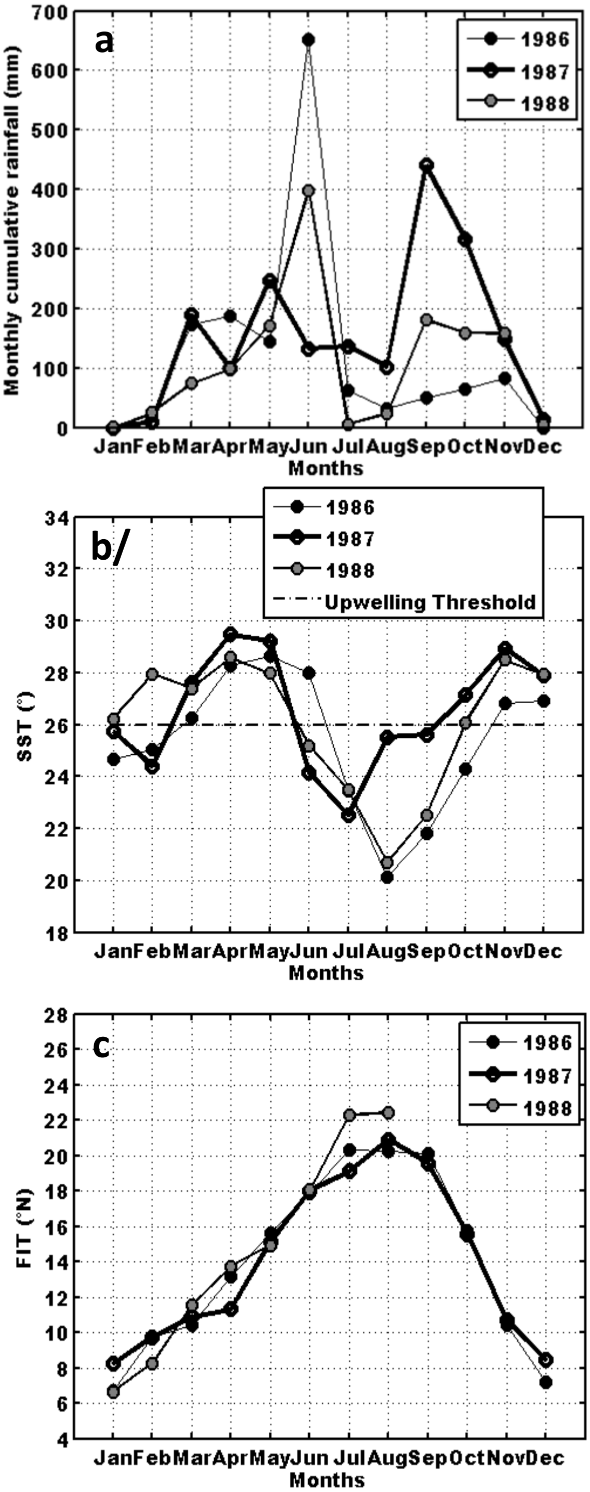

Fig. 2. Monthly and inter-annual variations of three climatic parameters: a/ Rainfall amount, b/ Sea surface temperature (SST) and, c/ Marker on the ground of the intertropical convergence zone (FIT). FIT data for 1988 do not cover the whole year (January to August)

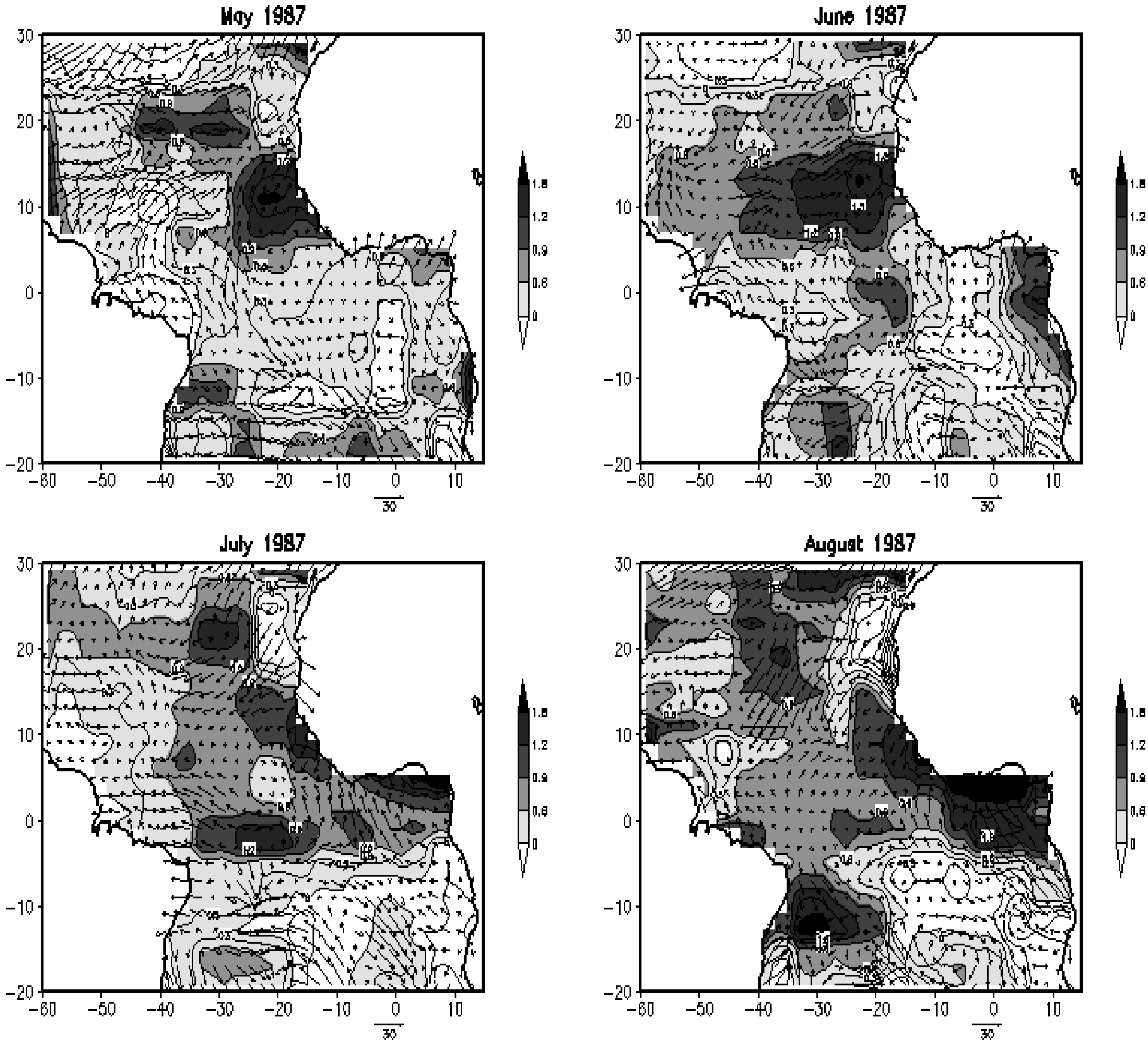

Fig. 3. Anomalies of the SST and the pseudo-winds stress of May, June, July and August 1987. The arrows are proportional to the intensities of the winds

Based on the year-to-year Atlantic Ocean Basin configurations with peak inversion implications, we also examined the seasonal and intra-seasonal behavior of the microstructure of precipitating convective systems in climate parameters such as SST and ITCZ. Specifically, we addressed the atypical year 1987 from ground measurements of raindrop size distributions.

3.2 SEASONAL VARIABILITY OF DSD

Fig. 4 shows the decadal evolution of the DSD parameters D_0, D_{max}, D_{min} (Fig. 4a), N_T, D_0/N_T and of the pre-factor A of the Z-R relationship (Fig. 4b), within the different seasons from the years 1986 to 1988. Through based on the analysis of these figures, it appears a good correlation between D_{min}, D_0, and D_{max} despite small variations of D_{min} and strong variability of the latter two. Similarly, it appears that the seasonal and decadal variability of the pre-factor A of Z-R is very close to the seasonal and decadal dynamics of the D_0/N_T parameter despite various combinations of individual variations in size and number of drops. However, the parameters A and D_0/N_T vary strongly over time while being well correlated. This result is similar to the one obtained by [14], [15] at the scale of the rainy events.

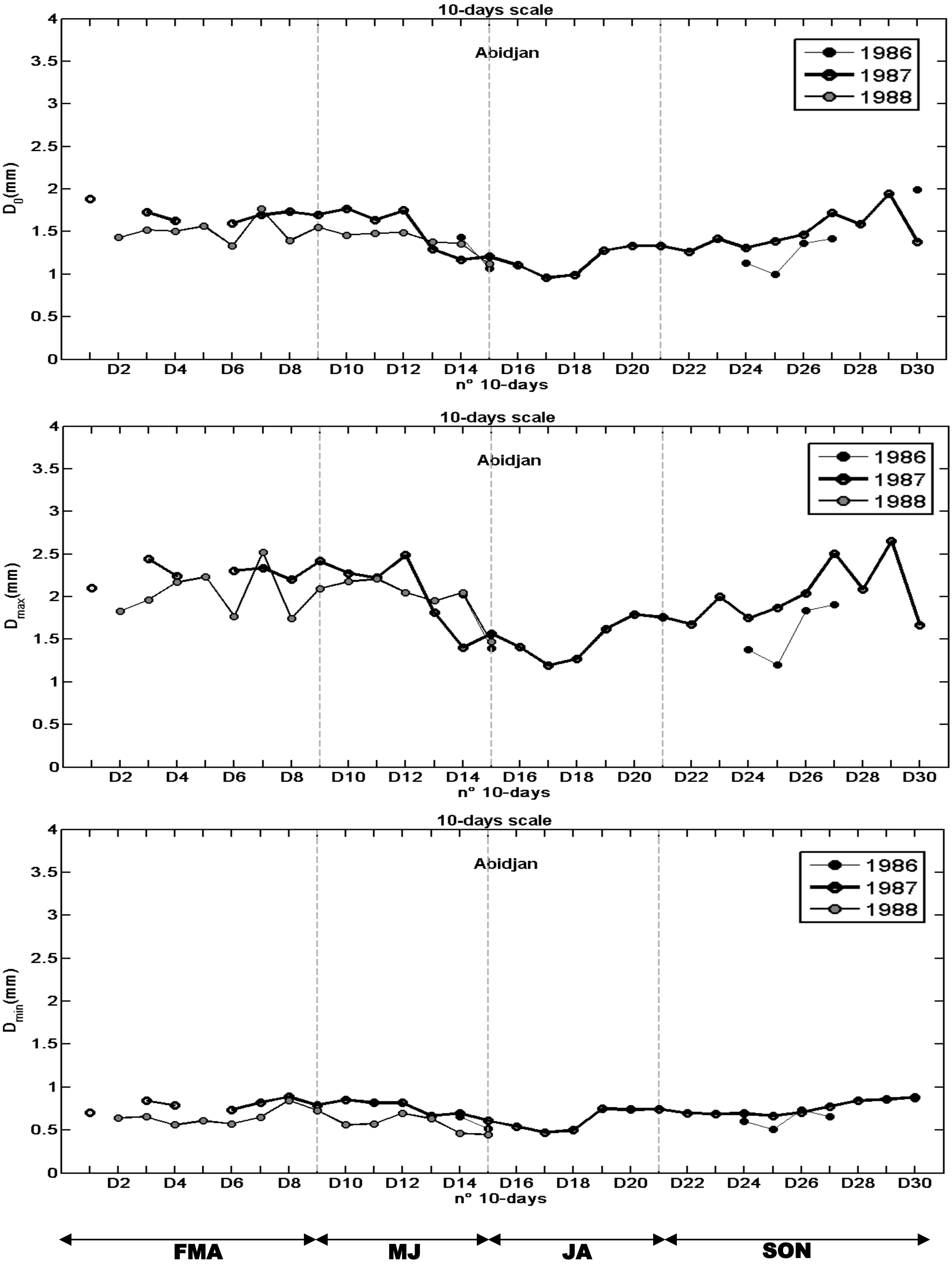

Fig. 4. a. Inter-annual, seasonal and decadal (10-days average) variations of rain drop size distribution (DSD) parameters (D_0, D_{max}, and D_{min}).

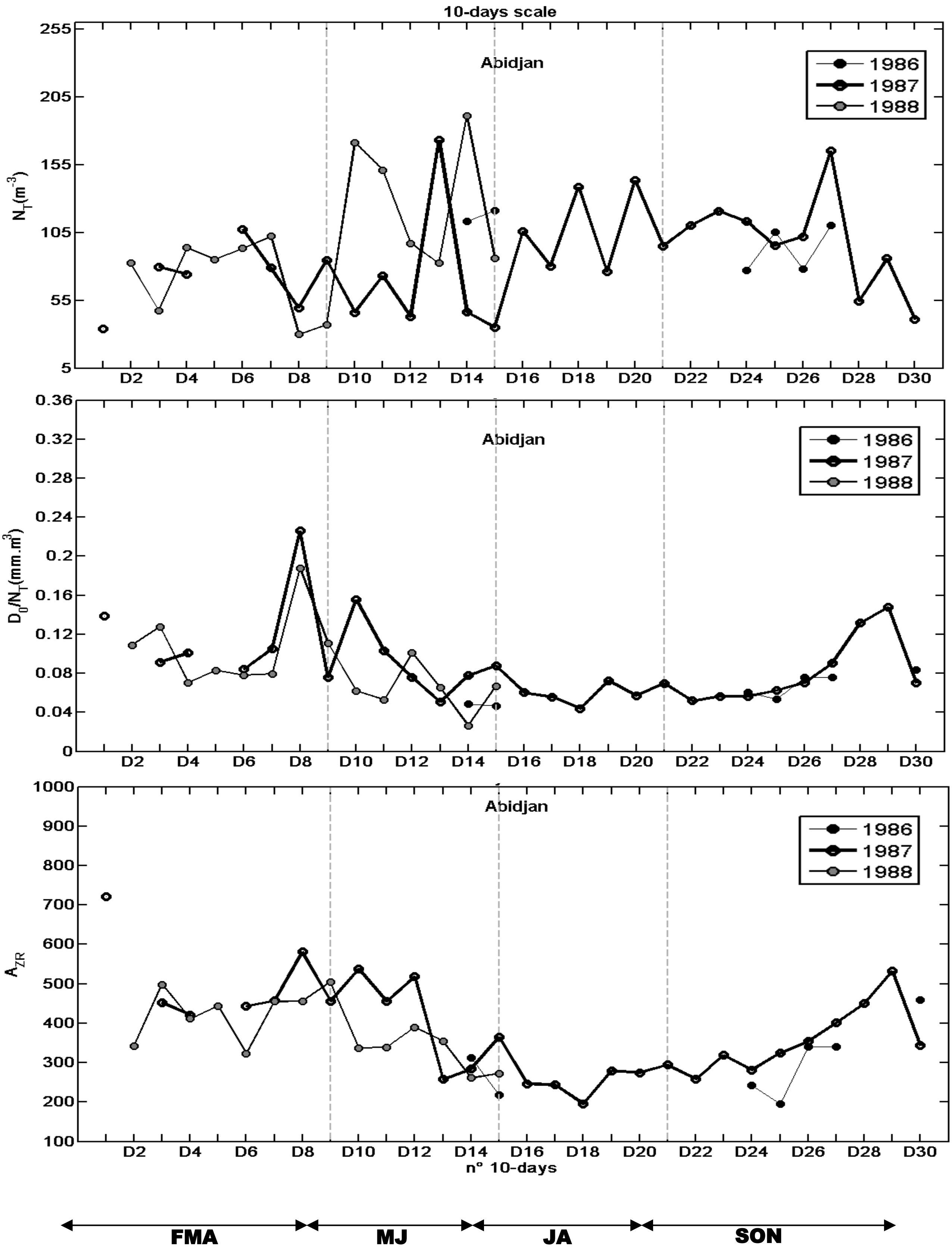

Fig. 4b. Idem Fig. 4a, but for the total number of drops N_T, the ratio between the diameter and the number of drops D_0/N_T and the pre-factor A of the power law Z-R

During the FMA season, the decadal fluctuations of A are more dependent on the variations in the number of drops, given the weakness of size variations. A decrease (increase) in the number of drops is associated with an increase (decrease) in the value of A. Therefore, on one hand, it varies in the same order as the D_0/N_T ratio. On the other hand, for the seasons MJ, JA, and SON, it is the simultaneous decadal fluctuations in the size and number of drops governing the variability of A.

As for the season JA in 1987, there is an increase in drops sizes (D_0 and D_{max}), D_0/N_T and A in August, all of them being of the same order of magnitude as those of September, which is the begining of the SON season. This situation therefore clearly shows the exceptional character of August 1987 which was particularly rainy as shown by the rainfall in Fig. 2 compared to the years 1986 and 1988 where August shows a low rainfall generally considered as normal. During the MJ and SON seasons, the characteristics of DSD in June 1987 (D_0 strong and N_T low) compared to those of October 1987 (D_0 strong and N_T strong) could explain the high rainfall recorded during SON compared to MJ where the rainfall is lower. Thus this justifies the inversion of seasonal peaks (Fig. 2). Moreover, D_0 and N_T behavior in these two seasons MJ and SON in 1986 and 1988 seem to be in contrast with those observed in 1987, which was described as an exceptional year by many previous studies [27], [28].

These results highlight the importance of considering an intra-season sampling method (pentad or decadal scales) in the understanding of the link between the nature of the rains, the dominant microphysical processes and the dsds produced by the precipitating systems. Understanding such a link is crucial for integrating the variability of DSD parameters into the calibration of ground-based or airborne radar-based rainfall estimation algorithms. To achieve this, an analysis of the vertical profiles of the DSD parameters and their evolution over time would be crucial to link them to a particular microphysical process as [30] did.

In Fig. 4, there is a clear variability in DSD parameters that can be compared with other climatic parameters, such as SST, which has similar variability (Fig. 5). More specifically, the characteristics of the beginning, the middle and the end of the season clearly differ from one to another, certainly in relation with the nature of the predominant systems during these periods. To explain such inter-seasonal changes, complex combinations of local factors should not be ruled out in conjunction with the global regional climate mechanisms prevailing during each season. To this end, an interesting exercise to do would be to compare the dsds to the SST and the East African waves (EAW) which, according to [18], represent the main typical phenomena of the synoptic scale associated with daily rains during the West African monsoon period.

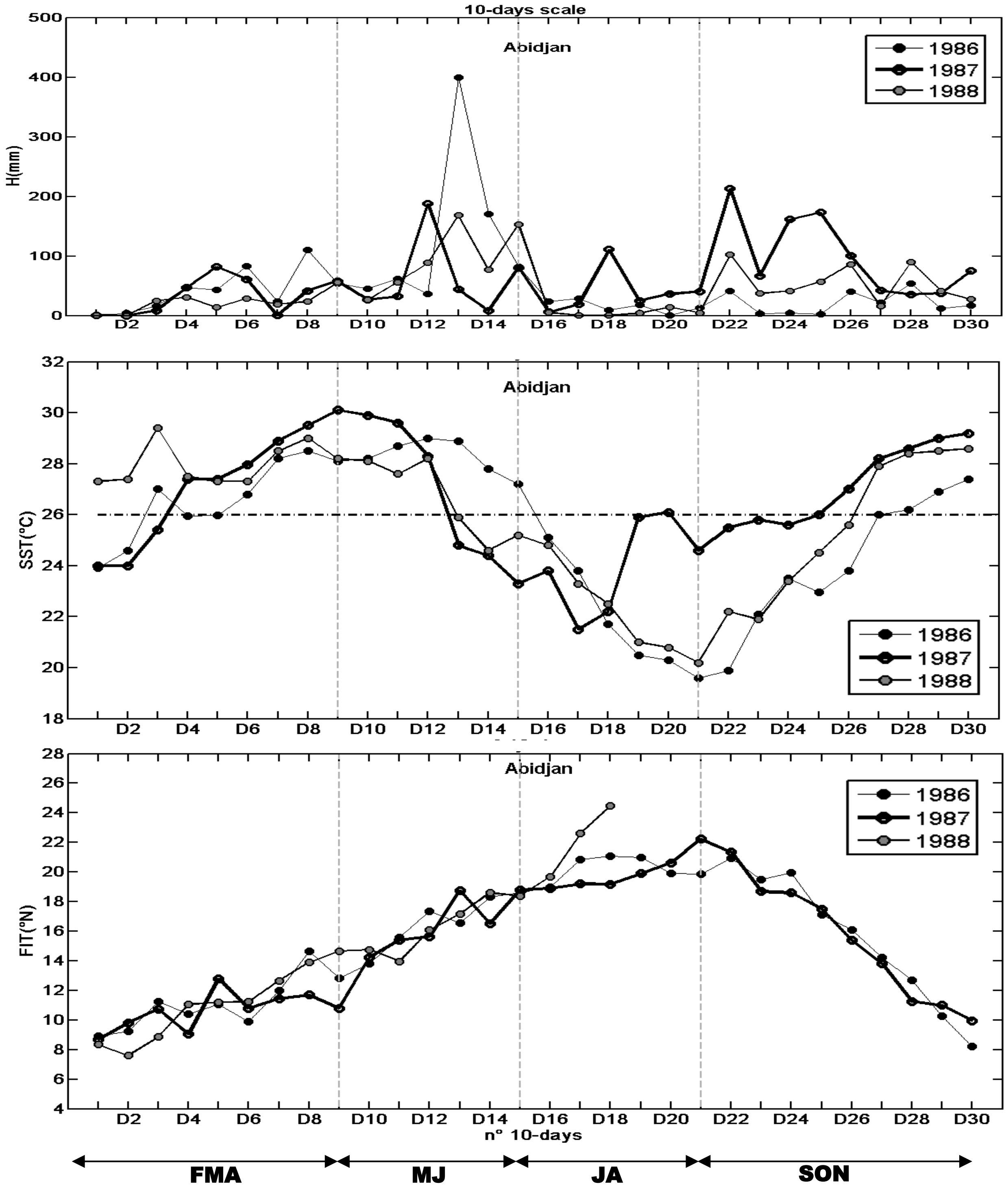

Fig. 5. ***Inter-annual, seasonal and decadal variations of climatic parameters: Rainfall amount (H), Sea Surface Temperature (SST), and marker at ground of ITCZ (FIT)***

On the basis of the variability modes analyzed above, we devoted the remaining of this work to carry out investigations making possible to compare the atypical nature of the year 1987, in particular with regard to the inversion of rain seasonal peaks, microstructure of precipitation systems and climatic parameters such as SST.

3.3 RELATIONSHIP BETWEEN SST AND DSD

To better understand the relationship between SST and the microstructure of precipitating systems, we focused on the dsds of June and October, which are the cores of the rainy seasons during MJ and SON in Abidjan [21], [27]. Based on the available data, only the average distributions following the adopted division are illustrated, for which at least two years of registration exist. For this purpose, the evolution per month, fortnight, decade and pentad of the dsds of the above-mentioned seasons were analyzed based on the work of [2], [3], who identified the same main modes of variability of the West African monsoon.

Fig. 6 (a, b, c and d) show for June and October, per fortnight, decade and pentad the averages of the dsds over the sampling times shown, for each year. For a better comparison, the average evolution (from June to October) is overlapped on the same figures at the same sampling steps of the SST. To illustrate the cold or warning of marine surface, we used 26°C as the threshold value (horizontal discontinuous line in Fig. 6, middle) suggested by [22] to characterise the coastal upwelling. Such a configuration makes possible the analysis together and more easily the variations of the two parameters of interest.

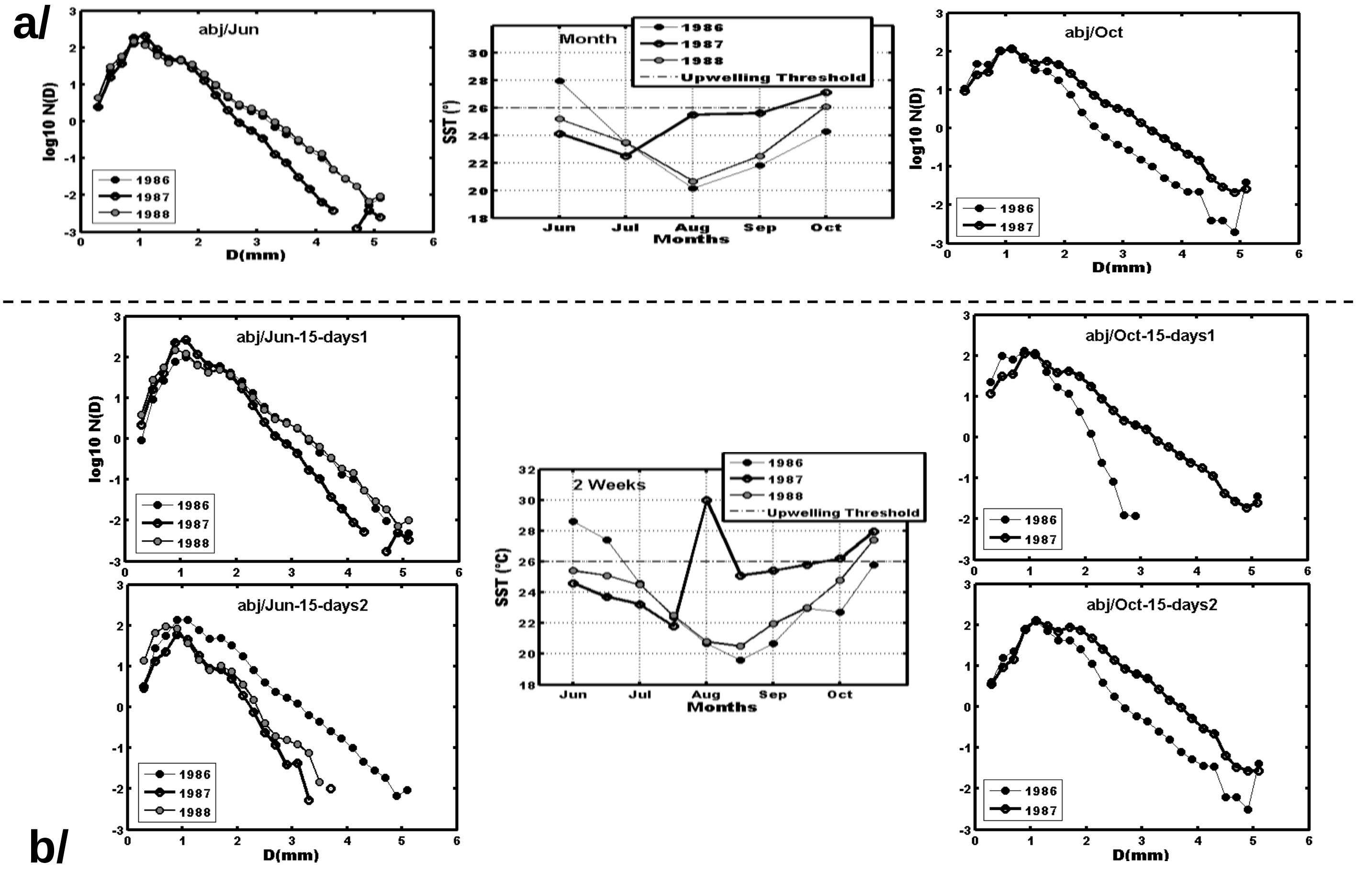

Fig. 6. Inter-annual variability of DSD and SST averaged monthly (a), and per 15-days (b) in Abidjan for June and October

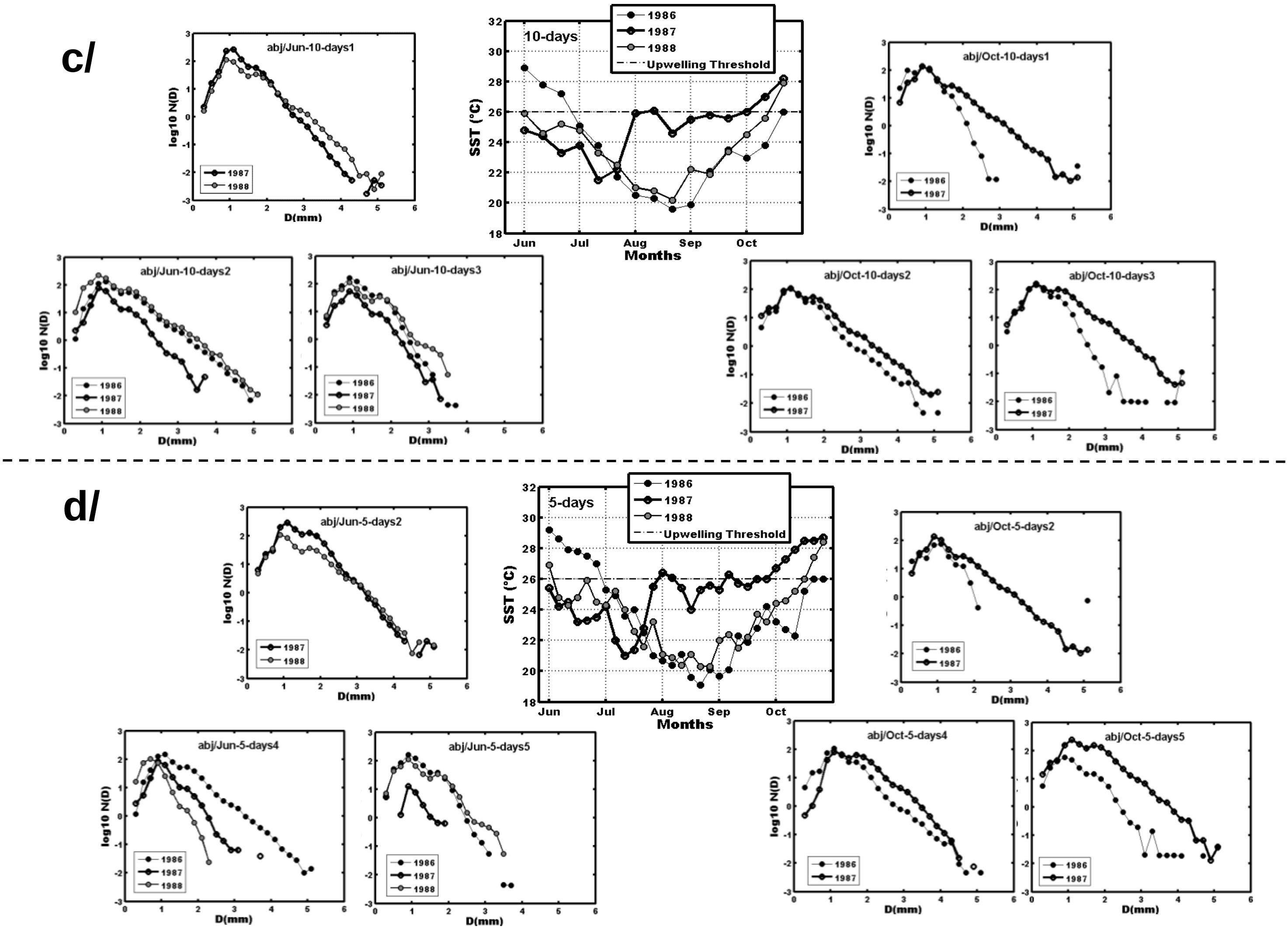

Fig. 6. Inter-annual variability of DSD and SST averaged decade or 10-days (c), and per 5-days (d) in Abidjan for June and October

The analysis of the figures (Fig. 6a) at monthly scale clearly shows the specificities in terms of the distribution of drops between one normal year (1986, 1988) and another atypical as 1987. For the normal years, the peak of the large rainy season MJ is marked by a larger number of large drops ($D \geq 2$ mm) than the atypical DSD of 1987. At the peak of the SON season, contrary to the behavior of the microstructure of rainy 1987 with DSD with larger drops than during the so-called normal years. The inversion of the rainfall peaks is therefore associated with the DSD in terms of the size of the drops. The SST analysis during these two months indicates a modulation of this inversion by Atlantic Ocean surface conditions. Generally, high SST induces important rain with spectra containing a large number of large drops due to strong convection associated with a large advection flow [29]. But, when SST is low, the spectra are devoid of large drops. Such situation is maintained and is better observed for sampling per 15-days (Fig. 6b), decade and pentad (Fig. 6c, d). Everything seems to indicate that lower SST values than the threshold of 26°C [22], that means coastal upwelling, would inhibit the dynamic convection of cloud cells [27]. In other words, the weak SST would favor the subsidence of the moist air masses and their horizontal spreading in contact with a lower colder layer due to its low recorded value (23°C) [31]. noted that cooling of marine surfaces reduces convection movements in the lower troposphere, which in turn leads to rainfall inhibition. In this context, according to [30], subsidence leads to the narrowness of DSD, as can be seen in the mean dsds of the pentads 4 of June 1987 and 1988, the pentad 6 of June 1987 and the pentad 2 of October 1986, all associated with low SST values. Moreover, a high SST values would favor the production of large raindrops, making the convective mechanisms in the hot phase more efficient, in particular, the coalescence resulting in more production of large drops in larger numbers [30].

4 CONCLUSION

This work illustrated the variability of the observed DSD over the coastal site of Abidjan at annual, seasonal and intra-seasonal scales. In general, low inter-annual variability tends to smooth seasonal and intra-seasonal fluctuations in the characteristics of raindrop size distributions. This variability is essentially driven by the N_T concentration parameter. However, we observed that depending on the season, there is a particular influence of D_0 (FMA and MJ to a lesser degree) or the combined combination of D_0 and N_T (JA and SON). This result justifies, once again, the simultaneous consideration of these two integrated parameters modulating the variation of radar rain estimation algorithms such as Z-R.

Finally, through these different analyses, we identify the atypical nature of 1987 compared to the years 1986 and 1988. Thus, we highlight the influence of SST on the microphysical processes at the base of training of dsds. On the basis of these results, the raindrop size distributions can be considered as relevant indicators to characterize the specific behaviour of the rainy seasons. Thus, in the context of subsequent studies on climatic variability, these results suggest that a few disdrometers for the systematic measurement of dimensional distributions of drops should also be associated with the classical rainfall measurement network.

ACKNOWLEDGMENTS

The authors are grateful to all of those who contributed to the data set used in this study, especially to Prof. H. Sauvageot who initiated EPSAT program and contributed strongly for the extension of the experiment to Abidjan (Côte d'Ivoire).

REFERENCES

[1] V. Mathon and H. Laurent, "Mesoscale convective system rainfall in the sahel", J. Appl. Meteor., Vol.41, pp.1081 – 1092, 2002.
[2] R. Roehrig, F. Chauvin, and J.-P. Lafore, "10–25-day intraseasonal variability of convection over the Sahel:.
[3] A role of the Saharan heat low and midlatitudes", *J. Climate*, vol. 24, pp. 5863–5878, 2011.
[4] D. E. Poan, R. Roehrig, F. Chauvin, and J.-P. Lafore, "West African Monsoon Intra-seasonal Variability: A Precipitable Water Perspective", J. Atmos. Sci., vol. 70, pp. 1035–1052, 2012.
[5] T. Iguchi, T. Kozu, J. Kwiatkowski, R. Meneghini, J. Awaka, and K. Okamoto, "Uncertainties in the rain profiling algorithm for the TRMM precipitation radar", J. Meteorol. Soc. Japan, vol. 87, pp. 1–30, 2009.
[6] T. Islam, A. M. Rico-Ramirez, M. Thurai, and D. Han, "Characteristics of raindrop spectra as normalized gamma distribution from a Joss-Waldvogel disdrometer", Atmospheric Research, vol. 108, pp. 57-73, 2012.
[7] R. Roca, H. Brogniez, P. Chambon, O. Chomette, S. Cloché, M. E. Gosset, J.-F. Mahfouf, P. Raberanto and N. Viltard, "The Megha-Tropiques mission: a review after three years in orbit", Front. Earth Sci., vol. 3, pp. 1–14, 2015.
[8] A. Y. Hou, R. K. Kakar, S. Neeck, A. A. Azarbarzin, and D. Christian, "The Global Precipitation Measurement (GPM) Mission", Bull. Am. Meteorol. Soc., vol. 95, pp. 701–722, 2008.
[9] H. Sauvageot and J. P. Lacaux, "The shape of averaged drop size distributions", J. Atmos. Sci., vol. 52, pp. 1070-1083, 1995.
[10] A. Nzeukou, H. Sauvageot, A. D. Ochou, C. M. F. Kebe, "Raindrop size distribution and radar parameters at Cape Verde", J. Appl. Meteorol., vol. 43, pp. 90-105, 2004.
[11] A. D. Ochou, A. Nzeukou, and H. Sauvageot, "Parametrization of drop size distribution with rain rate", Atmospheric Research, vol. 84, pp. 58-66, 2007.
[12] S. Moumouni, M. Gosset, and E. Houngninou, "Main features of rain drop size distributions observed in Benin, West Africa, with optical disdrometers", Geophys. Res. Lett., vol. 35, L23807, pp. 1-5, 2008.
[13] M. Gosset, E.-P. Zahiri, and S. Moumouni, "Raindrop size distribution variability and impact on X-band polarimetric radar retrieval: results from the AMMA campaign in Benin", Q. J. R. Meteorol. Soc., vol. 136 (s1), pp. 243-356, 2010.
[14] B. Russell, E. R. Williams, M. Gosset, F. Cazenave, L. Descroix, N. Guy, T. Lebel, A. Ali, F. Metayer, and G. Quantin, "Radar rain-gauge comparisons on squall lines in Niamey, Niger for the AMMA", Q. J. R. Meteorol. Soc., vol. 136 (s1), pp. 290-304, 2010.
[15] A. D. Ochou, E.-P. Zahiri, B. Bamba, and M. Koffi, "Understanding the variability of Z-R relationships caused by natural variations in raindrop size distributions (DSD): Implication of drop size and number", Atmospheric and Climate Sciences, vol. 1, pp. 147-164, 2011.
[16] B. Bamba, A. D. Ochou, E.-P. Zahiri, and M. Kacou, "Consistency in Z-R Relationship Variability Regardless Precipitating Systems, Climatic Zones Observed from Two Types of Disdrometer", Atmospheric and Climate Sciences, vol. 4 (5), pp. 941-955, 2014.

[17] T. Schneider, T. Bischoff, and G. H. Haug, "Migrations and dynamics of the intertropical convergence zone", Nature, vol. 513 (7516), pp. 45-53, 2014.
[18] S. E. Nicholson, "The ITCZ and the seasonal cycle over equatorial Africa", Bulletin of the American Meteorological Society, vol. 99 (2), pp. 337-348, 2018.
[19] S. Janicot, C. D. Thorncroft, A. Ali, N. Asencio, G. Berry, O. Bock, B. Bourles, G. Caniaux, A. Deme, L. Kergoat, J.-P. Lafore, C. Lavaysse, T. Lebel, B. Marticorena, F. Mounier, J.-L. Redelsperger, F. Ravegnani, C. E. Reeves, R. Roca, P. De Rosnay, H. Schlager, F. Chauvin, P. Nedelec, B. Sultan, M. Tomasini, A. Ulanovsky, and ACMAD forecasters team, "Large-scale overview of the summer monsoon over West Africa during the AMMA field experiment in 2006", Ann. Geophys., vol. 26, pp. 2569-2595, 2008.
[20] B. Sultan and S. Janicot, "The West African monsoon dynamics. Part II: The "pre-onset" and the "onset" of the summer monsoon", J. Climate, vol. 16, pp. 3407-3427, 2003.
[21] Y. Opoku-Ankomah, and I. Cordery, "Atlantic Sea-Surface Temperatures and Rainfall Variability in Ghana", J. Climate, vol. 7, pp. 551-558, 1994.
[22] K. Y. Kouadio, D. A. Ochou, and J. Servain, "Tropical Atlantic and rainfall variability in Côte d'Ivoire", Geophysical Research Letters, vol. 30, pp. 1-15, 2003.
[23] K. E. Ali, K. Y. Kouadio, E.-P. Zahiri, A. Aman, A. P. Assamoi, and B. Bourles, "Influence of the Gulf of Guinea Coastal and Equatorial Upwellings on the precipitations along its northern coasts during the Boreal Summer Period", Asian Journal of Applied Sciences, vol. 4 (3), pp. 271-285, 2011.
[24] M. Steiner, J. A. Smith, and R. Uijlenhoet, "A microphysical interpretation of radar reflectivity-rain rate relationships", J. Atmos. Sci., vol. 61, pp. 1114-1131, 2004.
[25] J. A. Smith, and W. F. Krajewski, "A modeling study of rainfall rate-reflectivity relationships", Water Resour. Res., vol. 29, pp. 2505-2514, 1993.
[26] J. Joss, and I. Zawadzki, "Raindrop size distributions again?", in Proc. 28th Conf. On Radar Meteorology, Seattle, WA, Amer. Meteor. Soc., pp. 1–6, 1997.
[27] A. Tokay, A. Kruger, and W. F. Krajewski, "Comparison of drop size distribution measurements by impact and optical disdrometers", J. Appl. Meteor., vol. 40, pp. 2083-2097, 2001.
[28] A. D. Ochou, M. Koffi, and H. Sauvageot, "Climatologie des distributions des gouttes de pluie en zone côtière ivoirienne", Publications de l'Association Internationale de Climatologie, vol. 12, pp. 252-260, 1999.
[29] J.-P. Lahuec and M. Carn, "Convergence intertropicale: l'intensité de la convection en juillet-août-septembre 1987", Veille Climatique Satellitaire, vol. 19, pp. 8-15, 1987.
[30] K. Y. Kouadio, K. E. Ali, E.-P. Zahiri, and A. P. Assamoi, "Etude de la prédictibilité de la pluviométrie en Côte d'Ivoire durant la période de Juillet à Septembre", Rev. Ivoir. Sci. Technol., vol. 10, pp. 117-134, 2007.
[31] D. Rosenfeld and C. W. Ulbrich, "Cloud microphysical properties, processes, and rainfall estimation opportunities", Radar and Atmospheric Science: A collection of essays in honor of David Atlas, Meteor. Monogr., vol. 30, pp. 237-258, 2003.
[32] K. Emanuel, "Increasing destructiveness of tropical cyclones over the past 30 years", Nature, vol. 436 (7051), pp. 686-688, 2005.