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Probability of dry and wet spells over West Africa during the summer monsoon season

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**This work aims at characterizing the conditional probability of single or consecutive dry and wet days in West Africa using the first-order Markov chain approach during the monsoon season (June to October). The results show that the probabilities of having a wet day (P_W), a wet day preceded by another wet day (P_{WW}) and a wet day preceded by a dry day (P_{DW}) are stronger in regions where the rainfall is maximum (mountain regions). In contrast, the probabilities of having a dry day (P_D), a dry day preceded by a wet day (P_{WD}) and a dry day preceded by another dry day (P_{DD}) are lower in the regions with higher precipitation. The seasonal cycle of P_{WW} (P_{DD}) is consistent with that of P_W (P_D), respectively in Western Sahel and Central Sahel regions. At the interannual timescale, MK test results show that P_W and P_{DW} (P_D and P_{DD}) exhibit statistically significant increasing (decreasing) trends the Western Sahel and the Central Sahel. Besides, the shorter dry spells (3 days) show statistically significant decreasing trends only in the Western Sahel. The longer dry spells (5, 7 and 10 days) show statistically significant downward trends over the Western and Central Sahel. Wet spells probabilities show non-significant decreasing trends in all sub-domains, except in the Western Sahel for the 10 days spells.
Knowledge of theses probabilities will contribute to develop efficient strategies for water resources management and agricultural decision making in West African countries.**

Key words: Markov chain, rainfall, occurrence, wet spell, dry spell, West Africa.

INTRODUCTION

Crop yields in West Africa depend mainly on the rainfall regime of the West African Monsoon (WAM). Knowledge of consecutive wet and dry days could be useful for the analysis of rainfall regimes in order to derive specific information necessary for crop planning and carrying out agricultural campaigns (Shahraki et al., 2013). According to the West Council and African Center for Agricultural Research and Development (Lamien, 2012) agriculture is the sector that continues to play a dominant role in the economy of West African countries representing more than 40% of their gross domestic product (GDP) and providing incomes and jobs for about 70% of the region's

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populations. Sarr and Camara (2018) found that climate change could have adverse effects on groundnut cultivation and that adaptation strategies will be essential for protecting this sector. West African agriculture is mainly influenced by the summer precipitation variability characterized by a succession of wet and dry days. Froidurot and Diedhiou (2017) have shown that the spatio-temporal variability of wet and dry episodes is linked to the spatio-temporal variability of the West African monsoon. Bichet and Diedhiou (2018a) found that the recent increase in rainfall over the entire West African Sahel band is mainly due to an increase in the number of wet days with more a strengthening of rainfall intensity in the central part of the subregions (Mali Niger Chad) and an increase of short dry spells occurrences. According to Taylor et al. (2017) the recent increase of the number of wet days and of the intensity of rainfall in the Central Sahel is associated with a tripled frequency of extreme Sahelian storms since 1982 due to global warming. Over the Gulf of Guinea and during the first rainy season (April-June) there is no significant trend observed in mean precipitation during the last thirty years but an increased occurrence of more intense rainfall is noted along the coast in agreement with the rise of the frequency of devastating floods. During the second rainy season (September-November) there is a significant increase in mean precipitation associated with an increase in precipitation intensity and frequency (Bichet and Diedhiou 2018b).

Wet and dry spells are among the most important rainfall variability characteristics as they affect water resources crop yields and food demand causing surpluses and deficits within a region (Biao and Alamou 2018; Ayanlade et al. 2018). Therefore the analysis of the rainfall should be done in terms of the probability of occurrence of these spells in the aim to tackle the climatic risk on crops in West Africa. This is justified by the fact that the agricultural sector is highly dependent on climatic conditions. It is therefore indispensable to develop a correspondence between the risk incurred by the agricultural sector and a climate risk model to facilitate the decision-making of policymakers (Stern and Cooper 2011). Effective forecasting of certain weather events such as the wet and dry spells is not easy. However the statistical study is a good tool to identify some aspects of rainfall variability (Mathoulthi and Lebdi 2008 2009). For instance the Markov chain is one of those tools that compute the probability of occurrence of an event knowing that it has occurred previously (Thirriot, 1986; Arnaud 1985). Many studies using the Markov chain in other regions exist in the scientific literature (Gabriel and Newman 1962; Todorovic and Woolhiser 1975; Katz 1977; Shahraki et al., 2013; Halder et al. 2016; Yoo et al. 2016; Bojar et al. 2018). For example Halder et al. (2016) used the Markov chain process to analyze the rainfall distribution in Eastern India. They showed that the probability of having two consecutive wet days varies

between 40 and 70% while the probability of having two consecutive dry days is between 50 and 90%.

In West Africa there are few studies using Markov chains to investigate the probability of dry and wet days (Raheem et al. 2015; Tettey et al., 2017; Biao and Alamou 2018; Doto et al. 2020). None of these studies focus on the analysis of the conditional probability of single or consecutive dry and wet days in the whole West African domain using the Markov chain. Previous analyses are local ones (or country level) and cannot represent the main characteristics of West African sub-domains rainfall. Climate information more specific to each domain of West Africa will be useful for better management of agriculture and water resources management.

The objective of this study is to analyze the conditional probabilities of wet and dry days and spells in West Africa with an emphasis on different sub-regions (Western Sahel Central Sahel Sudan and the Guinea Coast) of West Africa at different timescales (Intraseasonal to Interannual) using a first-order Markov chain.

DATA AND METHODS

We used daily rainfall data from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) for the period 1981 to 2020 with a spatial resolution of 0.25° x 0.25° (Funk et al. 2014; Poméon et al. 2017; Kouadio et al. 2018; Didi et al. 2020). This rainfall product is constructed from a combination of satellite observations and rain gauge station data like other rainfall products generally used in the West African region which is known to be a data sparse region: The Global Precipitation Climatology Project (GPCP) (Huffman et al. 2001) Global Precipitation Climatology Centre (GPCC) (Schamm et al., 2014) Climate Research Unit (Mitchell and Jones 2005) The Tropical Rainfall Measuring Mission (TRMM) (Huffman et al. 2007) etc. CHIRPS data were developed to support the United States Agency for International Development's Famine Early Warning Systems Network (FEWS NET). CHIRPS seasonal (July to September) climatology (Figure 1) shows a zonal distribution of rainfall with maxima located in the orographic regions (FD CM and JP). The lower seasonal rainfall amount is observed in the northern part of the domain (Sahel) and in the Guinea Coast.

In this present work the two state Markov chain of the first order was used that better describe the short-term persistence of rainfall occurrence in West African sub-regions from the intraseasonal to the interannual timescale. This method has been discussed by several authors (Stern and Cooper 2011; Afouda and Adisso 1997; Stern et al. 2006). Two states were used: dry day (D) and wet day (W). A day is considered to be dry (D) when the cumulative rainfall is less than 1 mm; while a wet day (W) is diagnosed when the rainfall amount is greater than or equal to 1 mm. Moreover the first-order two-state Markov chain is characterized by the fact that the current state depends only on the state of the previous period.

The different probability scores in this analysis are given and defined below. Equations 1 to 6 represent the initial and conditional probabilities (Pandharinath 1991; Shahraki et al., 2013; Dabral et al. 2014; Halder et al. 2016 Sifer et al., 2016).

Initial probability:

$$P_D = \frac{F_D}{N}$$

(1)
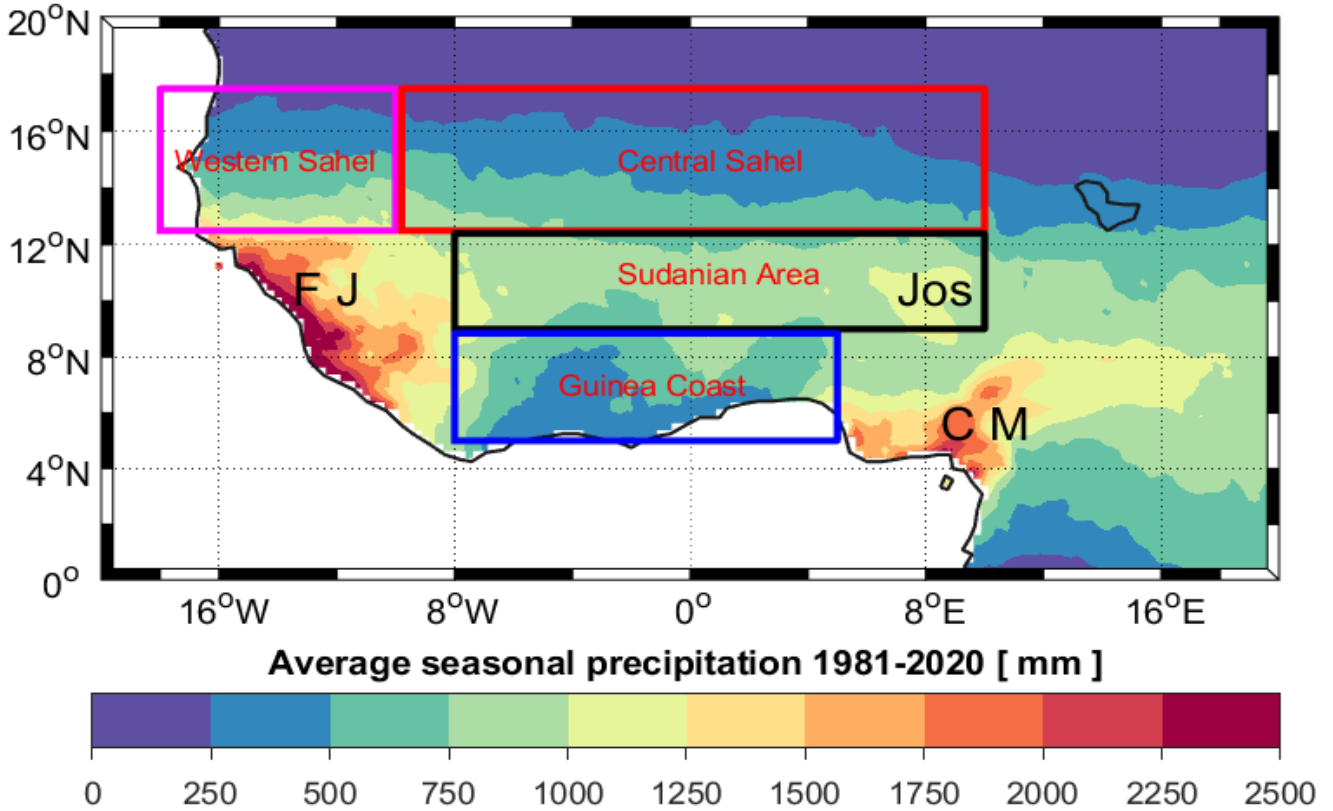
Figure 1. Average JAS seasonal precipitation (in mm) as observed with CHIRPS data for the period 1981-2020 over West Africa. The four colored rectangles indicate the considered sub-regions: Western Sahel (magenta) Central Sahel (red) Sudanian Area (black) and Guinea Coast (blue). The mountain areas are also shown: Fouta Jallon highlands (FJ) Jos Plateau (Jos) and Cameroon Mountains (CM).

$$P_W = \frac{F_W}{N} \tag{2}$$

Conditional probabilities

$$P_{DD} = \frac{F_{DD}}{F_D} \tag{3}$$

$$P_{WW} = \frac{F_{WW}}{F_W} \tag{4}$$

$$P_{DW} = 1 - P_{DD} \tag{5}$$

$$P_{WD} = 1 - P_{WW} \tag{6}$$

Where P_D is the probability of having a dry day P_W is the probability of having a wet day F_D is the number of dry days F_W is the number of wet days N is the number of days in the season P_{DD} is the (conditional) probability of having a dry day preceded by another dry day P_{WW} is the (conditional) probability of having a wet day preceded by another wet day F_{DD} is the number of dry days preceded by another dry day F_{WW} is the number of wet days preceded by another wet day P_{DW} is the (conditional) probability of having a wet day preceded by a dry day and P_{WD} is the (conditional) probability of having a dry day preceded by a wet day.

Thus the probabilities of a wet or dry day during n periods (Moon et al. 1994; Sonnadara and Jayewardene, 2015; Raheem et al. 2015; Raheem and Ezepue 2016; Nuga and Adekola 2018) are respectively:

$$P(W = n) = P_{WW}^{n-1}(1 - P_{WW}) \tag{7}$$

$$P(D = n) = P_{DD}^{n-1}(1 - P_{DD}) \tag{8}$$

At the interannual time scale trends are evidenced by linear regression ($y = ax + b$). A trend is characterized by an increase (a decrease) when the slope $a > 0$ (when $a < 0$).
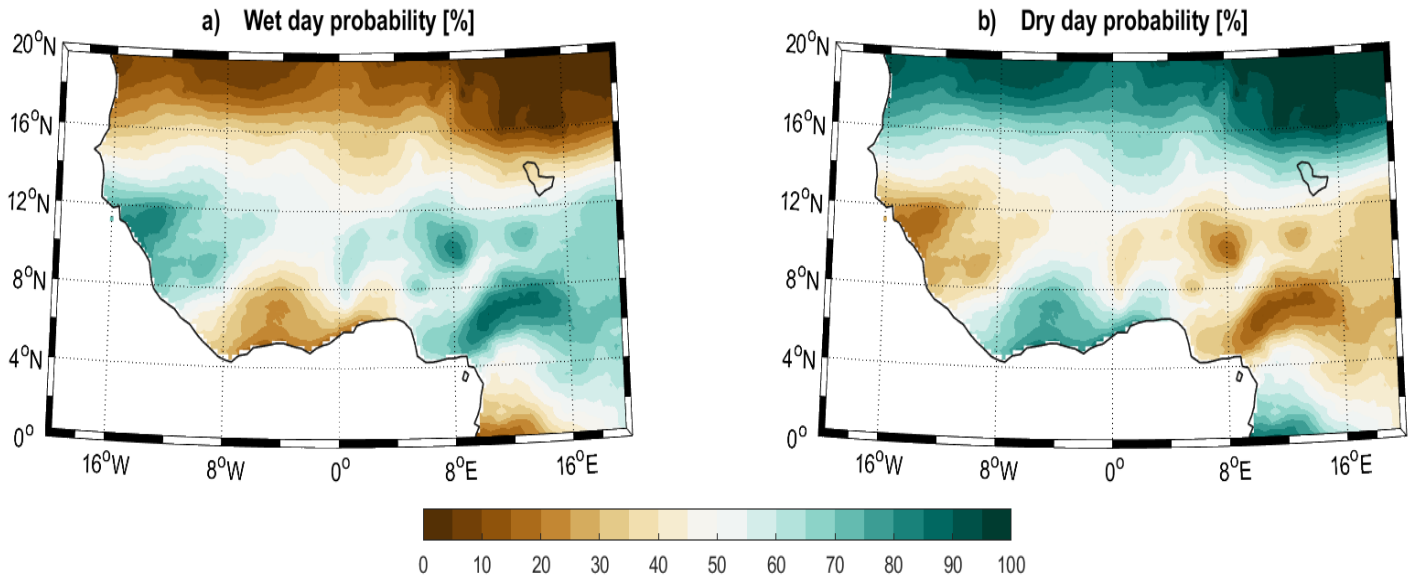
Figure 2. Probability (in %) of: (a) the wet day and (b) the dry day.

To detect statistically significant trends the nonparametric Mann-Kendall (MK) statistical test (Mann 1945; Kendall 1975) is used in this study. The test result H = 1 means a rejection of the null hypothesis at the alpha significance level. H = 0 means that the null hypothesis is not rejected at the alpha significance level. A typical value of alpha is 0.05 (Fatichi and Caporali 2009). If the p-value of the test is lower than alpha the test rejects the null hypothesis. If the p-value is greater than alpha there is insufficient evidence to reject the null hypothesis. The p-value of a test corresponds to the probability at the null hypothesis of obtaining a value of the test statistic as extreme as the value calculated from the time series data.

Figure 1 presents the study domain covering West Africa (20°W-20°E and 0-20°N) as in Froidurot and Diedhiou (2017). In this region rainfall follows a North-South gradient with the annual mean rainfall ranging between 400 mm in the Northern part (Northern Sahel) and more than 1500 mm in the South along the Guinea Coast. The highest annual mean rainfall is observed over mountain regions such as the Fouta Djallon the Adamawa Mountain between Nigeria and Cameroon and the Jos Plateau in central Nigeria.

We analyzed the spatio-temporal variability of the probabilities using four sub-regions represented in Figure 1 which are the Western Sahel (18°W-10°W; 12.5°N-17.5°N) the Central Sahel (10°W-10°E; 12.5°N-17.5°N) the Sudanian Zone (8°W-10°E; 9°N-12.5°N) and the Guinea Coast (8°W-10°E; 5°N-9°N). The mean annual precipitation in these sub-regions is respectively 575 430 1047 and 1247 mm (Froidurot and Diedhiou 2017). Rainfall patterns follow the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ). They are also associated with the northward movement of the monsoon flow over the continent (Sultan et al. 2007). The Guinean Coast has two rainy seasons (from April to July and from September to October) while the Sahel domain (Western Sahel and Central Sahel) is characterized by a single rainy season located roughly between June and October.

The occurrence of wet and dry spells is evaluated for different intervals of duration (3 5 7 and 10 days) as in Sivakumar (1992) and Froidurot and Diedhiou (2017). These intervals are selected to be consistent with the African Easterly Waves (AEWs) synoptic disturbances which are known to modulate the daily rainfall in West Africa during the summer (Diedhiou et al., 1998; Wu et al., 2013).

RESULTS AND DISCUSSION

Spatial variability of the probabilities of wet and dry days

Figure 2 shows the spatial distribution of the probabilities of having a rainy day and a dry day during the summer season from July to September (JAS). The spatial variability of the probability of having an isolated single wet day (Figure 2a) is similar to that of seasonal precipitation (Figure 1) marked by a latitudinal gradient. The highest values are observed in the orographic regions (Fouta Jallon highlands Jos plateau and Cameroon Mountains). This distribution can be explained by the influence of the mountains and the latitudinal migration of the Inter-tropical Convergence Zone (ITCZ). The maximum probability in these orographic (mountains) areas is around 90% meaning that on average 83 days out of 92 days are wet in the season. Over these regions the orographic forcing of moisture fluxes leads to a stronger convective activity (intensity and frequency) (Sall et al. 2007). The probability of having an isolated wet day varies from more than 50% in the sahelian regions to less than 30% in the Gulf of Guinea. As for the probability of having a dry day (Figure 2b) low values are found in areas of high rainfall (that is Fouta Jallon highlands Jos Plateau and Cameroon Mountains) and stronger values in regions of lower annual rainfall (over the northern Sahel and the Guinea Coast). The spatial variability of conditional probabilities (P_{WW} P_{WD} P_{DW} and P_{DD}) are displayed in Figure 3. Figure 3a shows a spatial distribution of P_{WW} with high values located over the orographic regions (Fouta Jallon highlands Jos plateau
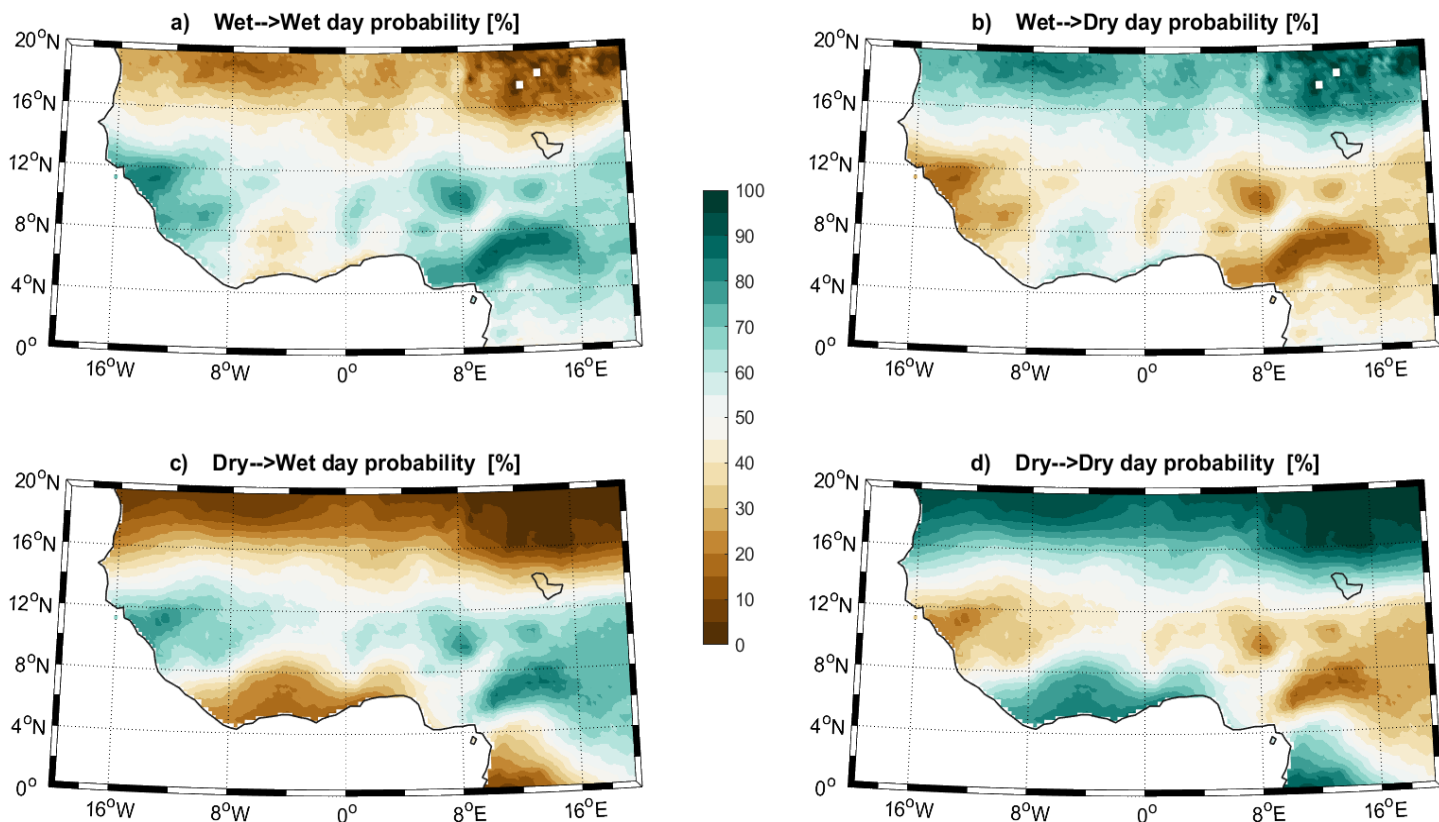
Figure 3. Transition probabilities (in %) of: a) wet day to wet day b) wet day to dry day c) dry day to wet day and d) dry day to dry day.

and Cameroon Mountains). Low values of P_{WW} are observed in the northern part of the Sahel and over the Guinea Coast. Conversely an opposite distribution is present when considering P_{WD} (Figure 3b) with low probabilities located over the orographic regions and high probabilities north of the Sahel and over the Guinea Coast. P_{DW} (Figure 3c) shows a distribution quite similar to that of P_{WW} with high values localized in mountainous areas and low ones north of the Sahel and over the Guinea Coast. However P_{DD} (Figure 3d) remains weak over the orographic regions. The high P_{DD} value is observed over the northern Sahel and the Guinea Coast. The strongest values of P_{DD} in the Guinea Coast are explained by the fact that the JAS period corresponds to the short dry season (or little dry season associated with a decrease of precipitation) in this region.

Figure 4 presents the spatial variability of the probabilities of consecutive rainy days of length 3 5 7 and 10 days. The spatial distribution of the probability to obtain 3 consecutive wet days (Figure 4a) is different from that of the mean seasonal precipitation with low values found over the orographic regions (Fouta Jallon

highlands Jos plateau and Cameroon Mountains). This means that the number of shorter wet spells are lower in these areas during the monsoon season (JAS) compared to other regions. Besides low probability values are found over the Guinea Coast in coherence with the decrease of precipitation during this season (little dry season) while North of 12.5°N the probability of having three (3) consecutive wet days varies up to 16% (that is over Senegal). Shorter wet spells are higher in the driest areas (Froidurot and Diedhiou 2017) that is in the sahelian regions. The patterns of the probability of occurrence of longer wet sequences (Figure 4b-d) exhibit a latitudinal gradient. They are higher in the same areas as those of the seasonal average precipitation (that is over the orographic regions). This result highlights the role of the orography (mountain) in the occurrence of these longer rainfall episodes. Their probabilities strongly decrease when the duration of the sequence becomes longer and are concentrated over the orographic regions; the probabilities of 7-10 days spells are lower than 4%.

Figure 5 presents the spatial variability of the probabilities of consecutive dry days. The probability of occurrence of short dry spells (Figure 5a) varies up to 16% in the whole region except in orographic areas where it reaches 4%. The probabilities of longer sequences (Figure 5b-d) are high in the northern Sahel
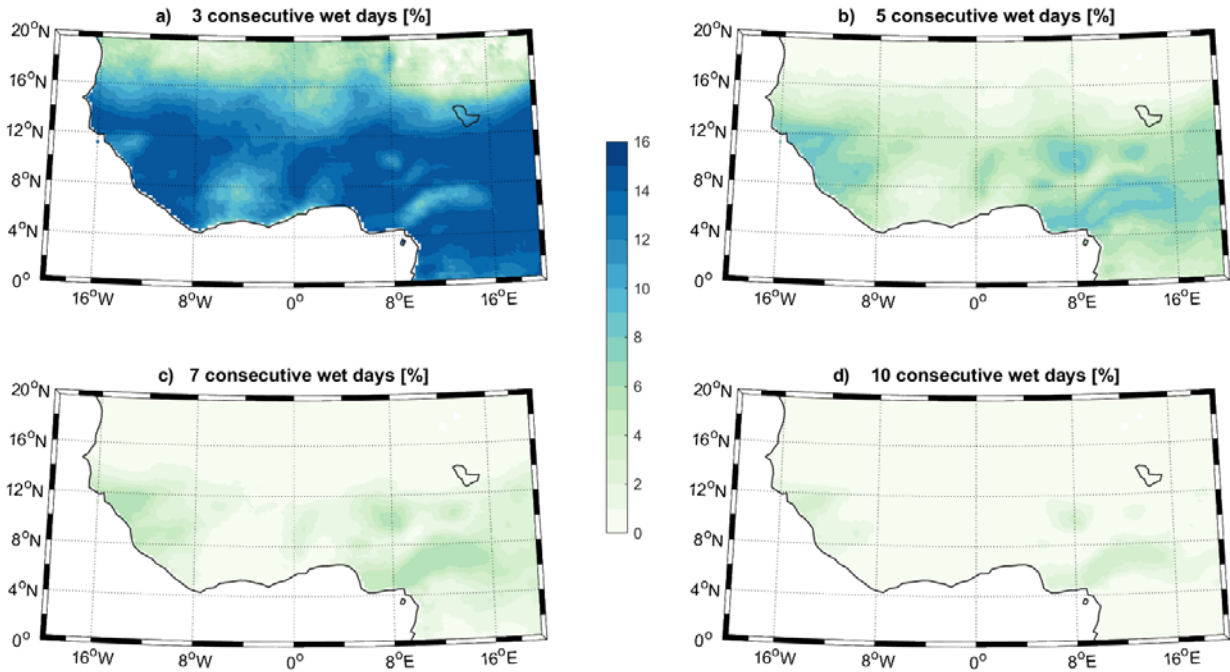
Figure 4. Probabilities (in %) of: a) 3 days wet spells length b) 5 days wet spells length c) 7 wet days spells length and d) 10 wet days spells length.
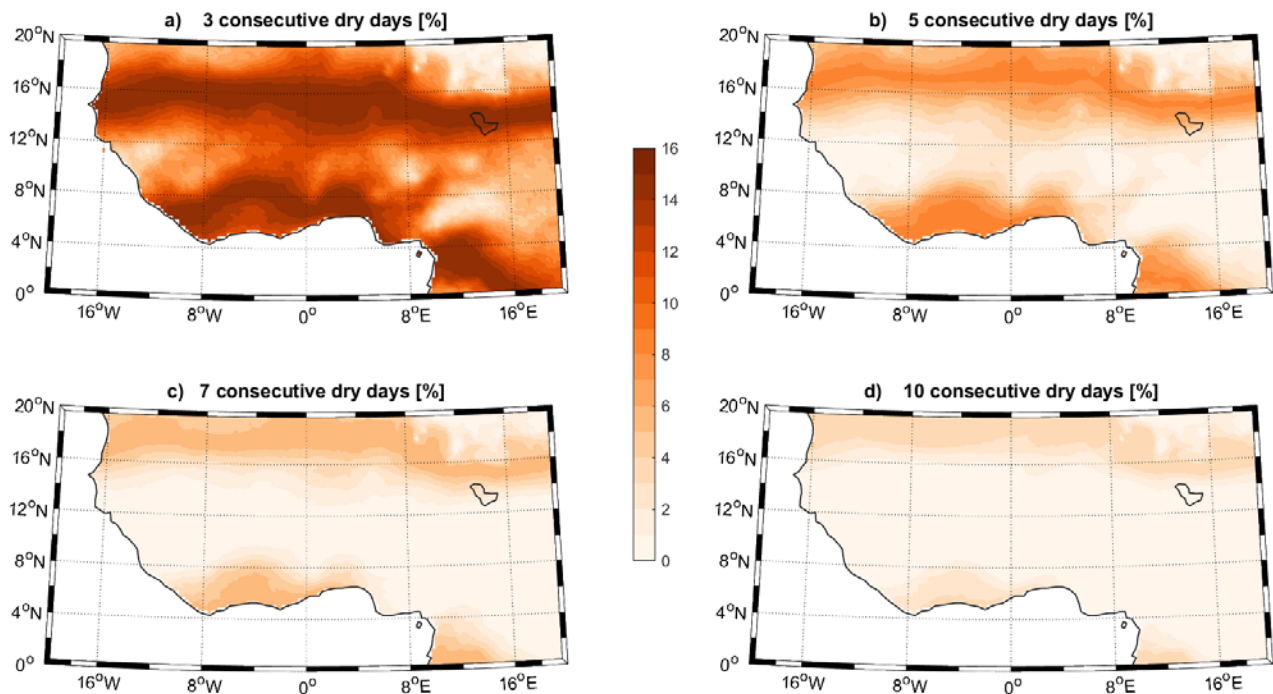
Figure 5. Probabilities (in %) of : a) 3 days dry spells length b) 5 days dry spells length c) 7 days dry spells length and d) 10 dry days spells length.

and the Guinea Coast and vary up to 9%. Like wet spells the probabilities of dry spells become lower when considering longer sequences. Overall the highest probability values are encountered for short dry spells (3
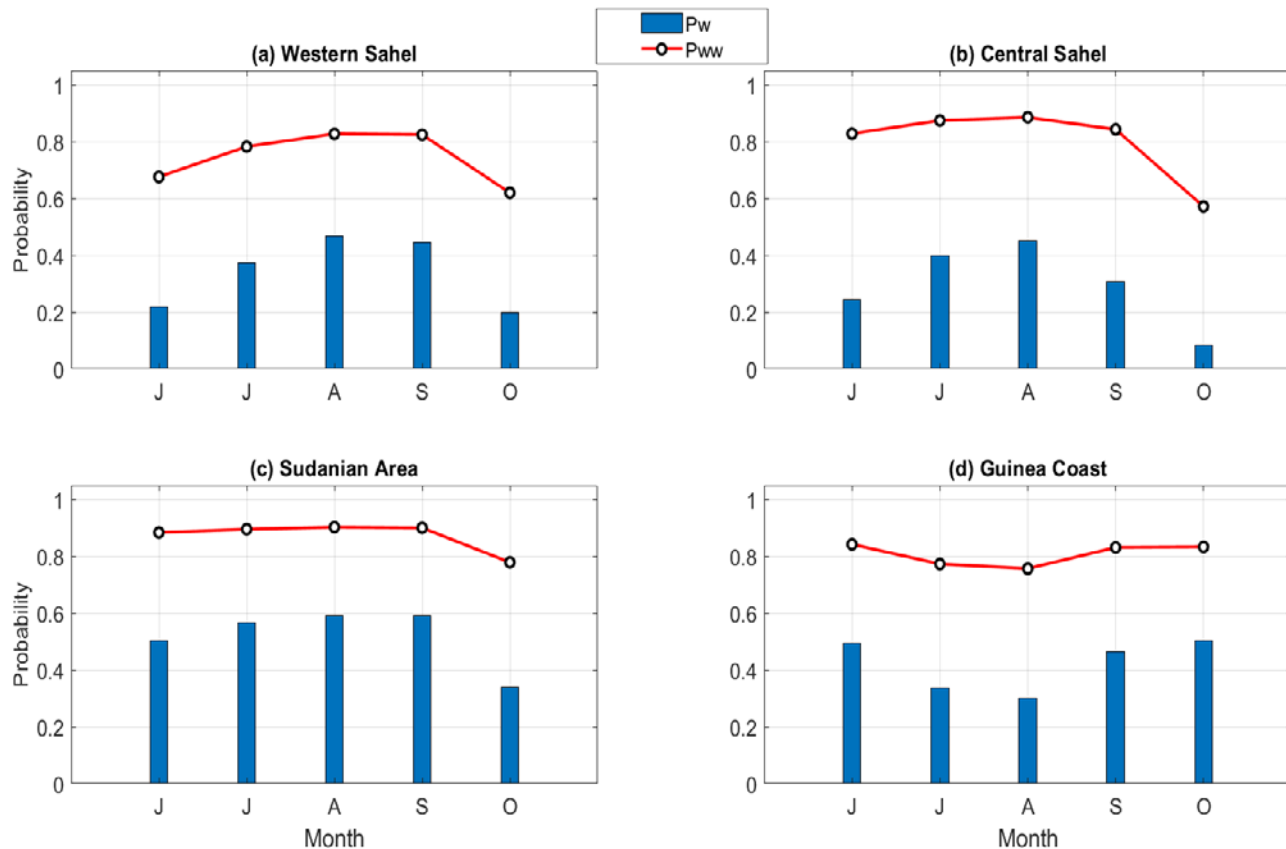
Figure 6. Seasonal cycle of the transitional probabilities (curve; P_{WW}) and the probability of wet days (histogram; P_W) for the sub-domains.

and 5 days) over the sahelian regions and the Guinea Coast. Longer dry spells (7 and 10 days) have low probabilities (<4%) in the same areas. These results concerning the spatial variability of wet and dry sequence probabilities are consistent with those described in Froidurot and Diedhiou (2017) for the same regions.

The analysis of wet and dry spells can help to better understand the occurrence of floods and drought. A better detection characterization and prediction of these spells are crucial for agriculture in West Africa. This sector is known to be highly dependent on monsoon rainfall and represents a significant amount of the GDP. The information on rainfall probabilities is vital for the design of water management supplementary irrigation projects and the evaluation of alternative cropping systems for effective soil water management plans.

Seasonal cycle of transition probabilities

Figures 6 and 7 present the seasonal cycle (from June to October) of transition probabilities of P_{WW} and P_{DD} (respectively from wet-to-wet and dry-to-dry respectively).

The other two transition probabilities of P_{WD} and P_{DW} (from wet-to-dry and dry-to-wet respectively) can be inferred from these two probabilities respectively (Appendix Figures 1 and 2).

Figure 6 shows that the seasonal variation of the transition probabilities of P_{WW} is consistent with that of wet days probability (P_W) in all considered sub-domains. The higher probability values are observed during the July-August-September period in the sahelian regions (Western Sahel and Central Sahel) and in the Sudanian area coinciding with the core of the monsoon season in those areas; the maximum appears during August. These months concentrate most of the annual rainfall amount in the Sahel-Sudan region as well as most of agricultural activities. Over the Guinea Coast the transition probability of wet spell (P_{WW}) shows two maximums. The first (second) maximum is observed in June (October) coinciding with the precipitation core of the first (second) rainy season in this area. The lowest P_{WW} is observed in August. The first and the second maximum of P_W in this
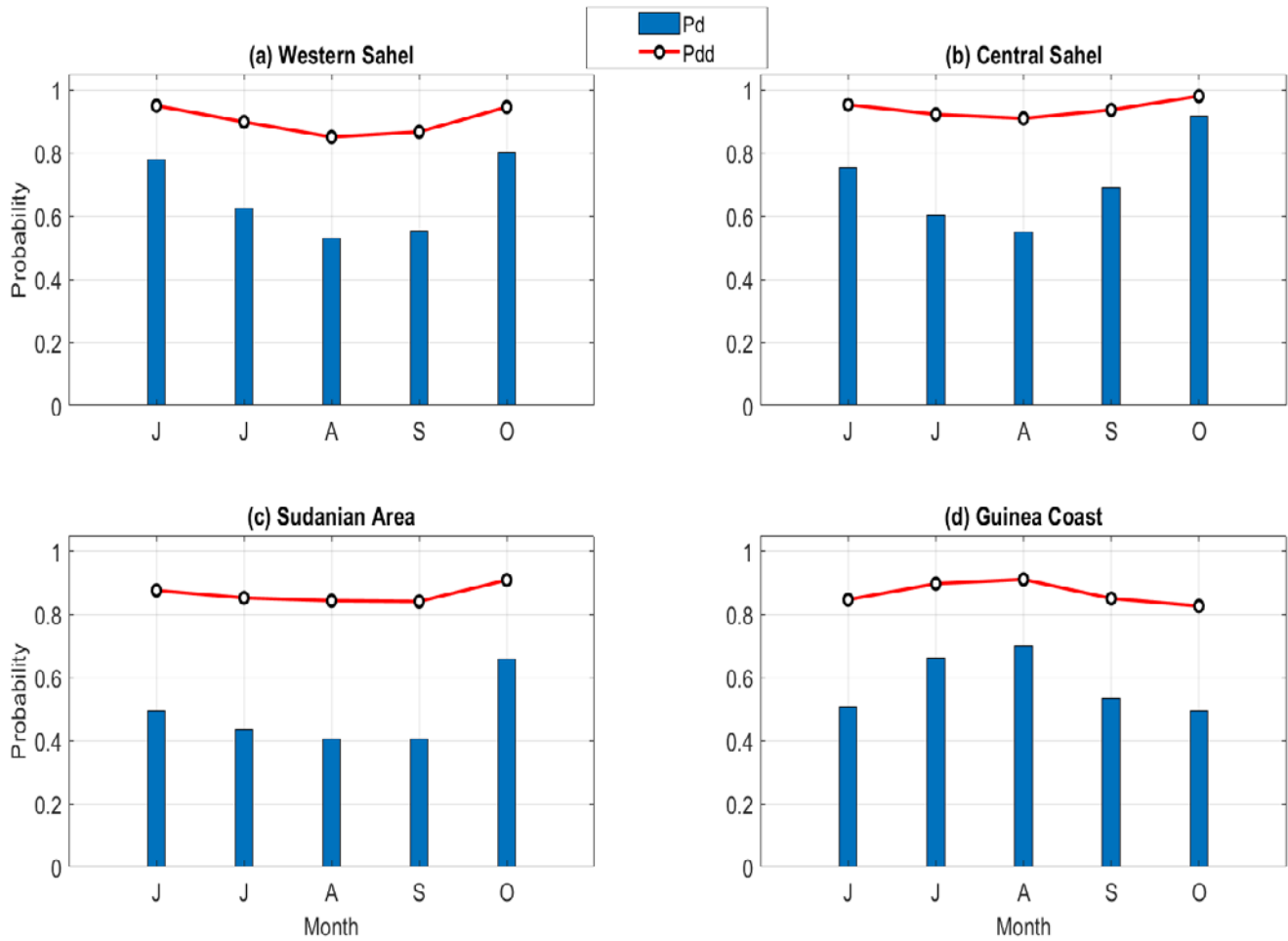
Figure 7. Seasonal cycle of the transitional probabilities (curve; P_{DD}) and the probability of dry days (histogram; P_D) for the selected sub-domains.

area corresponds to the same months (that is June and October respectively) as for P_{WW}. Therefore the transition probability of dry spells (P_{DD}) (Figure 7) shows the low values during the months where the probabilities of P_{WW} are high (that is JAS) in all sub-regions excepted in the Guinea Coast.

The probability of dry days (P_D) is consistent with P_{DD} in those regions. In the Guinea Coast the observed variation of transitional probabilities (P_{DD}) is consistent with the probability of dry days (P_D). The highest probabilities values are observed during July August and September due to a decrease in precipitation (that is the little rainy season) in this region. Our results on the seasonal transition probability of P_{WW} and P_{DD} in the sudano-sahelian regions are consistent with those of

Doto et al. (2020) in Burkina-Faso.

Interannual variability of the probabilities of wet and dry days

Here the analysis of the interannual variability of rainfall events probabilities on each of the considered sub-regions is presented.

Figure 8 presents the results of the probabilities of wet and dry days during the summer season (JAS). The probability of having a wet day (Figure 8a) varies between 33.23 and 50.76% over the Western Sahel 25.61 and 50.72% over the Central Sahel 47.76 and 66.83% over the Sudanian Zone and 25.43 and 60.16% over the Guinea Coast. Besides P_W showed a significant increase trend in the Western (p-value = 0.00005) and the Central Sahel (p-value = 0.00008) and non-significant increase trend in the Sudanian Zone (p- value = 0.9350)
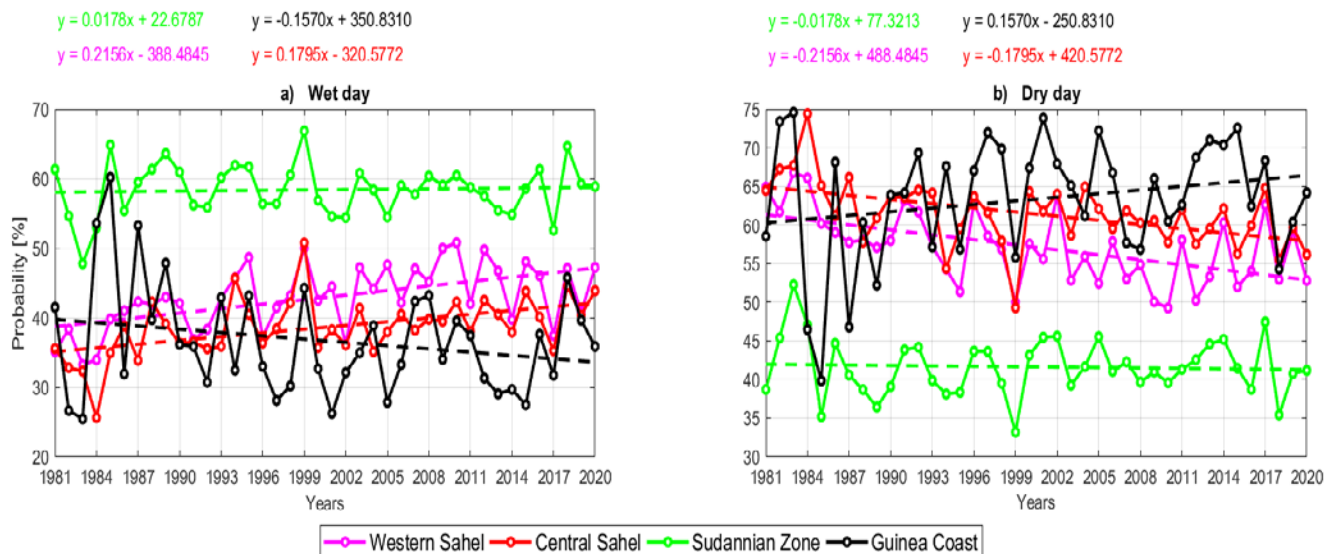
y = 0.0178x + 22.6787   y = -0.1570x + 350.8310

y = 0.2156x - 388.4845   y = 0.1795x - 320.5772

y = -0.0178x + 77.3213   y = 0.1570x - 250.8310

y = -0.2156x + 488.4845   y = -0.1795x + 420.5772

Figure 8. Probabilities of wet day (a) and dry day (b) over the period 1981-2020.

Table 1. Initial and transition probabilities of dry and wet days over West African sub-regions in the summer period (JAS).

Sub-region	Transition probability				Initial probability	
	P_{WW}	P_{WD}	P_{DD}	P_{DW}	P_{W}	P_{D}
Western Sahel	0.4709	0.5291	0.5932	0.4068	0.4291	0.5709
Central Sahel	0.4017	0.5983	0.6157	0.3843	0.3860	0.6140
Sudanian Area	0.5762	0.4238	0.4090	0.5910	0.5838	0.4162
Guinea Coast	0.4567	0.5433	0.6813	0.3187	0.3667	0.6333

while a non-significant decrease trend is observed in the Guinea Coast (p-value = 0.3822).

As for the probability of having a dry day it varies between 49.24 and 66.77% over the Western Sahel 49.28 and 74.39% over the Central Sahel 33.17 and 52.24% over the Sudanian Zone and 39.84 and 74.57% over the Guinea Coast (Figure 8b). Also P_{D} showed statistically significant decrease trends in the Western and Central Sahel.

Overall Table 1 shows that the probability of an isolated rainy day remains high in the Sudanian Zone (58.38% on average) compared to the other zones while the probability of having a dry day remains low (41.62% on average). The highest probability of having an isolated dry day is observed in the Guinea Coast (63.33% on average).

The transition probability analysis is shown in Figure 9. The probability of P_{WW} (transition from wet-to-wet) varies between 36 and 55.42% in the Western Sahel 34.27 and 50.68% in the Central Sahel 48.43 and 66.38% in the Sudanian Zone and 32.44 and 66.67% in the Guinea

Coast (Figure 9a). A downward and non-significant trend is observed in the Sudanian zone and the Guinea Coast while an upward and non-significant trend is observed in the Western Sahel and the Central Sahel (Figure 9a). As for the probability of P_{WD} it varies between 44.58 and 64% in the Western Sahel 49.32 and 65.73% in the Central Sahel 33.62 and 51.57% in the Sudanian Zone and 33.33 and 67.56% in the Guinea Coast (Figure 9b). As the P_{WW} the P_{WD} showed non-significant trends for all West African areas (Figure 9b).

The probability P_{DW} varies between 28.12 and 52.53% in the Western Sahel 22.12 and 52.07% in the Central Sahel 44.81 and 69.35% in the Sudanian Zone and 23.03 and 50.20% in the Guinea Coast (Figure 9c). The P_{DW} showed significant (non-significant) upward trends in the Western Sahel and Central Sahel (Sudanian zone) while a decrease and a non-significant trend is noted in the Guinea Coast. As for P_{DD} it ranges between 47.47 and 71.88% 47.93 and 77.88% 30.65 and 55.19% and 49.80 and 76.97% respectively over the Western Sahel
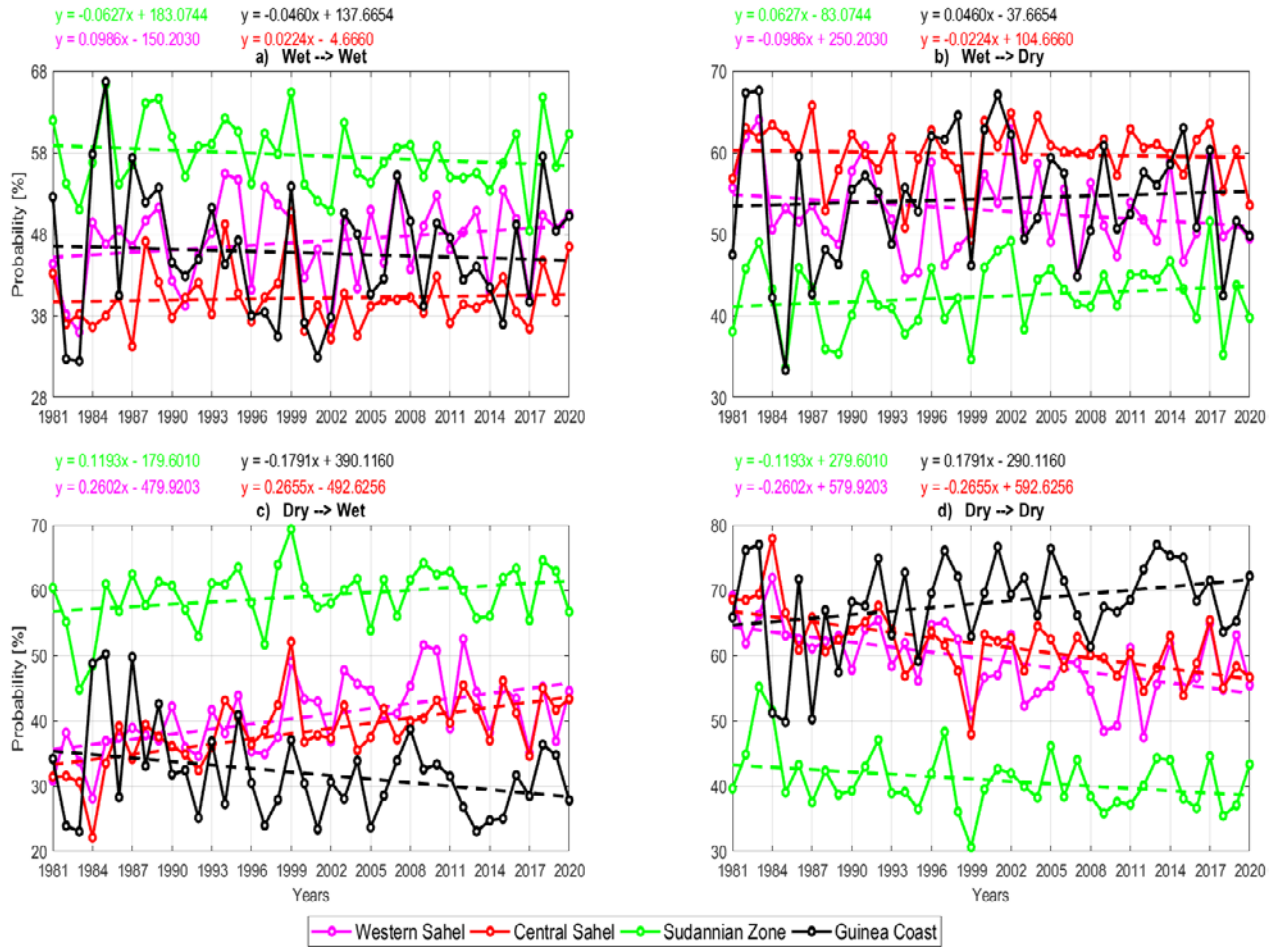
Figure 9. Transition probabilities. (a) Wet day to wet day (b) wet day to dry day (c) dry day to wet day and (d) dry day to dry day.

the Central Sahel the Sudanian Zone and the Guinea Coast (Figure 9d). Contrary to the trends of P_{DW} the P_{DD} exhibited significant (non-significant) downward trends in the Western Sahel and Central Sahel (Sudanian zone) while a non-significant increase trend is noted in the Guinea Coast. Overall in the Western Sahel and Central Sahel the P_{DW} have increased during these last thirty years. This means that the Sahel is becoming wetter confirming the recovering of the rainfall (associated with an increase of rainy days occurrence and intensities) (Nicholson 2005; Taylor et al. 2017; Bichet and Diedhiou 2008a). Taylor et al. (2017) demonstrate that due to global warming the frequency of extreme Sahelian storms tripled since 1982.

However Table 1 reveals that the probabilities of having two successive dry days (P_{DD}) are higher than having a dry day followed by a wet day (P_{DW}) in all considered sub-domains except the Sudanian Zone. On the other hand the probability of having a wet day followed by a dry day (P_{WD}) is higher than that of having two successive wet days (P_{WW}). The highest probability of having two successive dry days is observed in the Guinea Coast (68.13% on average). This high probability may be due to a rainfall decrease during the JAS season over this area of West Africa. However the highest probability of having two successive wet days is recorded in the Sudanian Zone (57.62% on average). Our results on the transition probabilities are in agreement with those of Biao and Alamou (2018) who showed that the probabilities of having two successive dry days are stronger than those of having a dry day followed by a wet day and the probabilities of having two successive wet days are much lower than the probabilities of having a wet day followed by a dry day at all stations studied in Benin. Our results are also consistent with those found by Rahem et al. (2015) in Nigeria and Tettey et al. (2017) in the south eastern coastal belt of Ghana (that is Cape Coast Akatsi Keta Akuse and Accra). According to Selvaraj and Selvi (2011) knowledge of these probabilities can reduce the risk associated with meteorological uncertainty which
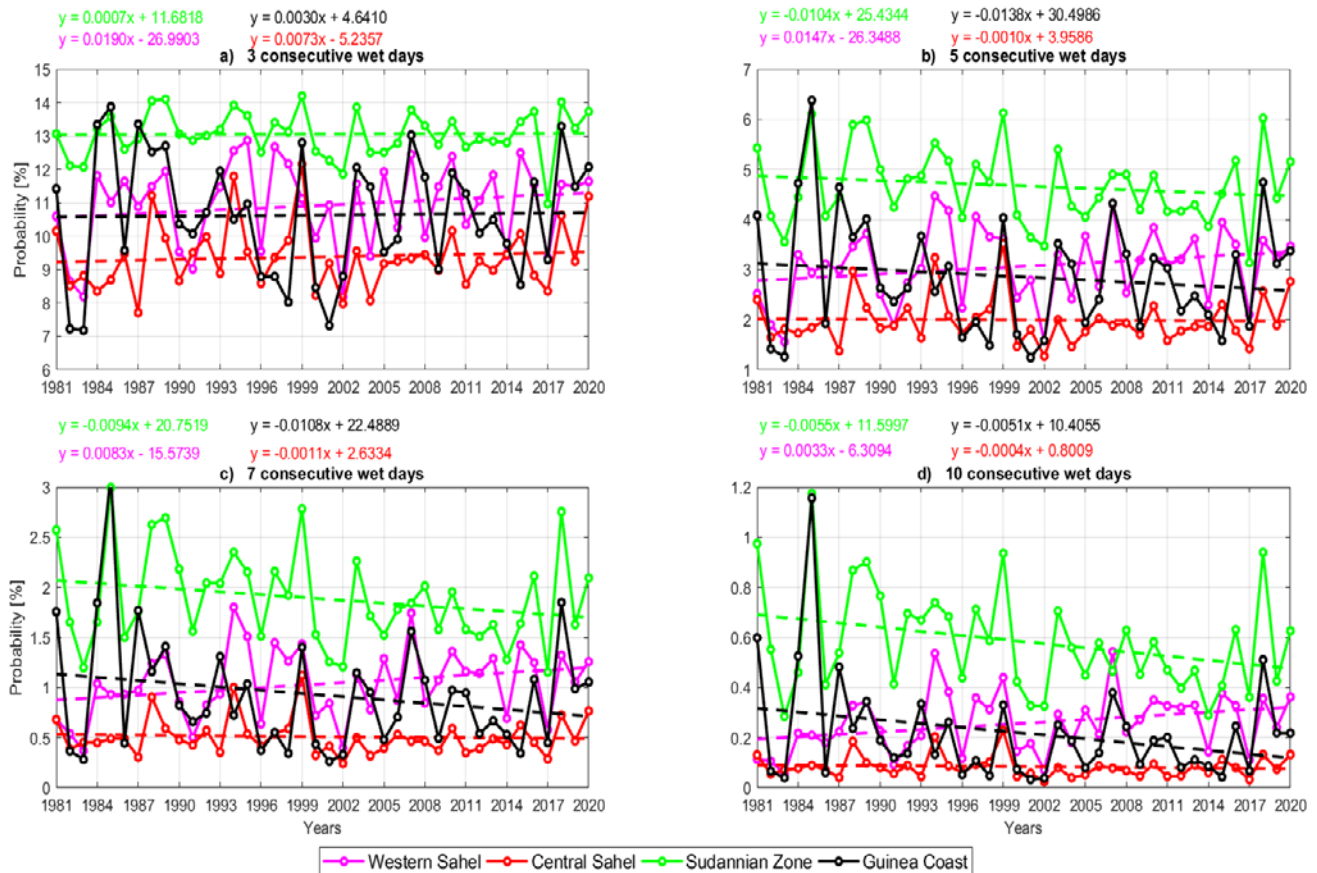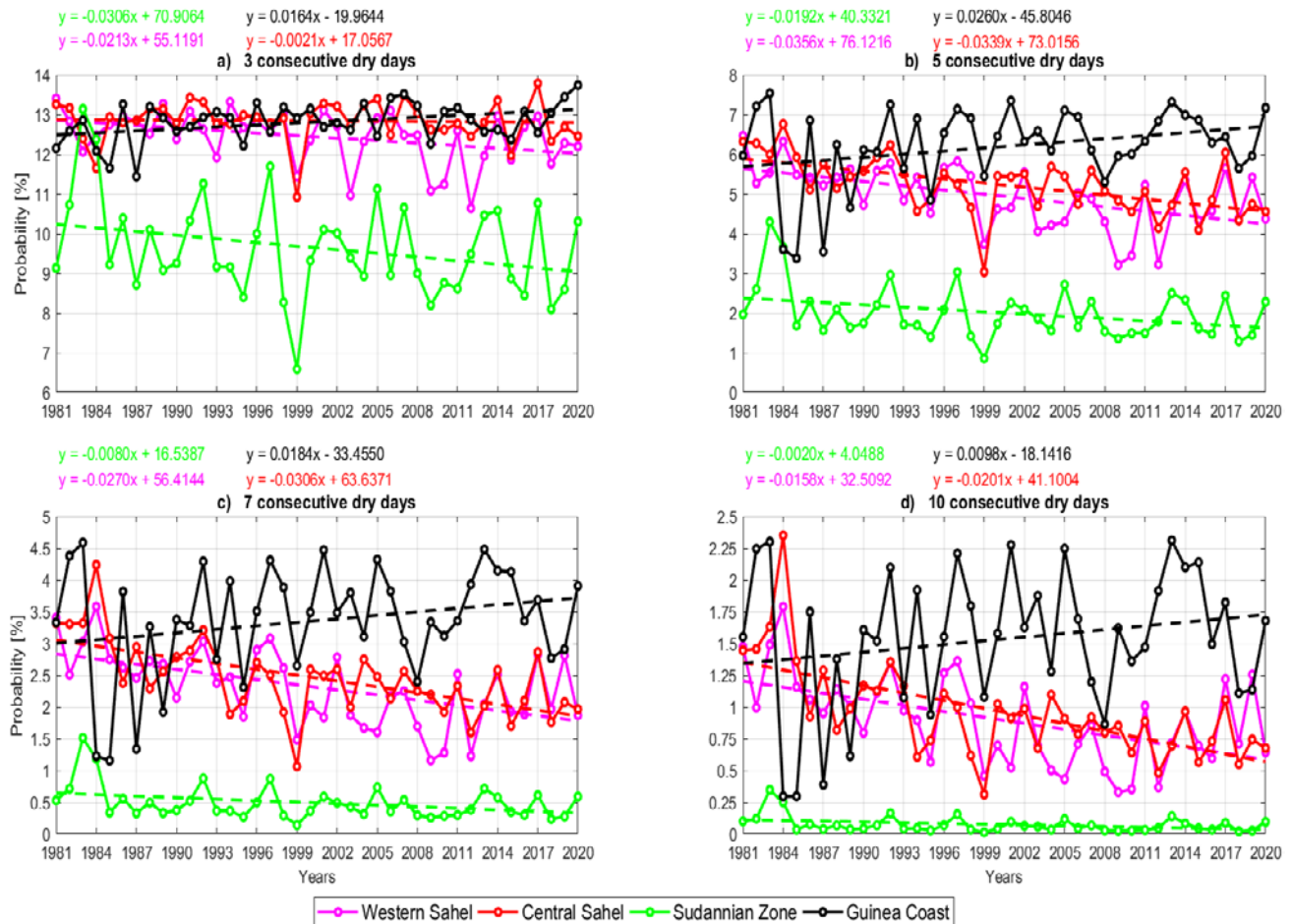
Figure 10. Consecutive wet day's probability. (a) 3 consecutive wet days (b) 5 consecutive wet days (c) 7 consecutive wet days and (d) 10 consecutive wet days.

in turn is fundamental because it can help policymakers take appropriate water management decisions for food security.

Analysis of the interannual variability of wet and dry spells is displayed in Figures 10 and 11 respectively. When considering the wet spells (Figure 10) the probability of occurrence of 3 consecutive wet days varies between 8.18 and 12.87% in the Western Sahel 7.71 and 12.16% in the Central Sahel 10.97 and 14.20% in the Sudanian Zone and between 7.18 and 13.88% in the Guinea Coast. The probability values decreased gradually for wet sequences of increasing length (Figure 10b c d). The probability of the occurrence of consecutive wet days remains high in the Sudanian zone regardless of the length of the considered wet sequence. Overall the Western and Central Sahel show an increasing trend of the probabilities of occurrence of consecutive wet days whatever the duration while the Sudanian Zone and the Guinea Coast show a decreasing trend during these thirty years. The probabilities of consecutive wet days showed non-significant trends for all studied areas except the Western Sahel where the 10 consecutive wet days show a significant increase trend (p-value = 0.0192).

The analysis of dry spells interannual variability (Figure 11) shows that the P_{3D} (Figure 11a) varies between 10.64 and 13.40% 10.92 and 13.78% 6.59 and 13.14% and 11.44 and 13.74% respectively over the Western Sahel the Central Sahel the Sudanian Zone and the Guinea Coast. As observed in Figure 11 the probability of consecutive dry days (for all durations) has a decrease trend in all studied areas except the Guinea coast where the increase trend is observed. The P_{3D} exhibits significant trends only in the Western Sahel (p-value = 0.0231). These probabilities decrease when the sequence becomes longer (Figure 11b c d). The longer dry spells (5 7 and 10 days) show statistically significant trends over the Western Sahel and the Central Sahel. In the Sudanian Zone only the 10 consecutive dry days show statistically significant trend (p-value = 0.0490). In Guinea Coast the probability of longer dry spells exhibits a non-significant trend. The Mann-Kendall test results for different West African sub-domains are summarized in Appendix Table 1. The Sudanian Zone experienced the weakest values of consecutive dry days. This difference in the spatio-temporal variability of the probabilities could

Figure 11. Consecutive dry day's probability. a) 3 consecutive dry days b) 5 consecutive dry days c) 7 consecutive dry days et d) 10 consecutive dry days

Table 2. Probabilities of consecutive dry and wet days over West African sub-regions during the summer season.

Subregions	Consecutive wet day probabilities				Consecutive dry day probabilities			
	P_{3W}	P_{5W}	P_{7W}	P_{10W}	P_{3D}	P_{5D}	P_{7D}	P_{10D}
Western Sahel	0.1093	0.0306	0.0104	0.0026	0.1244	0.0494	0.0231	0.0090
Central Sahel	0.0938	0.0199	0.0051	0.0000	0.1284	0.0522	0.0246	0.0096
Sudanian Area	0.1306	0.0467	0.0189	0.0058	0.0964	0.0200	0.0049	0.0000
Guinea Coast	0.1063	0.0285	0.0092	0.0022	0.1281	0.0620	0.0336	0.0154

be due to the meridional movement of the Intertropical Convergence Zone (ICTZ). Table 2 summarize the characteristics of dry and wet spells probability and shows that the mean of 3 consecutive wet (dry) days probability is 0.1093 (0.1244) in the Western Sahel 0.0938 (0.1284) in the Central Sahel 0.1306 (0.0964) in the Sudanian Zone and 0.1063 (0.1281) in the Guinea Coast. These results indicate that there is probably more drought persistence in the rainy season in parts of West

Africa (Western Sahel Central Sahel and Guinea Coast) except the Sudanian Zone. This drought persistence may cause a shortage of river flows hence of water resources and water availability activities in agro-pastoral areas (Biao and Alamou 2018). The succession of dry days may be the combined result of the decrease in the intensity of rainfall and the number of wet days during the summer monsoon season in these regions (Western Sahel Central Sahel and Guinea Coast). This information

can have potential benefits for the water resource management and agricultural decision making.

Conclusion

The Markov chain process was used to evaluate the initial conditional and consecutive wet and dry day probabilities during the monsoon season in West Africa. The results can be summarized as follows:

1) When considering the intra-seasonal variability the probability of having an isolated wet (dry) day remains high (low) in regions with higher precipitation (Sahel and Sudan regions). The probabilities of P_{WW} and P_{DW} are stronger over the orographic regions while P_{DD} and P_{WD} values are lower in these same areas. The probability of consecutive wet days decreases when the sequence becomes longer and is stronger over the orographic regions. As for the wet days the probability of consecutive dry days becomes lower when the sequence is longer but is almost zero in the orographic regions.

2) The analysis of the seasonal cycle shows that the variation of P_{WW} is similar to that of P_W in all sub-regions except the Guinea Coast with high values observed in the core of the rainy season (that is July to September). Besides the seasonal variation of P_{DD} is similar to that of P_D in all West African considered sub-regions.

3) At the interannual timescale the probability of having an isolated wet (dry) day exhibits a significant increase (decrease) trend in the Western Sahel and the Central Sahel. However these probabilities are not statistically significant in the Sudanian zone and in the Guinea Coast. Regarding the analysis of conditional probabilities our results showed that P_{DD} (P_{DW}) exhibits a substantial statistically significant decrease (increase) trend in the Western and Central Sahel. The probability of P_{WW} and P_{WD} are statistically non-significant in West Africa regions. The probability of shorter dry spells (3 days) show significant downward trends only in the Western Sahel. In addition longer dry spells (5 7 and 10 days) show statistically significant downward trends over the Western Sahel and the Central Sahel and only the 10 consecutive dry days which show statistically significant decrease trend in the Sudanian Zone. In the Guinea coast the probability of dry spells show a non-significant upward trend.

Future work is planned to study on one hand the changes in these probabilities in a near future (2040-2060) and in a far future (2080-2100) using climate projections and on another hand to characterize these changes under 1.5 and 2°C global warming.

For this purpose a goodness-of-fit test of the Markov chain (Besag and Mondal 2013) will be applied to CMIP5 and CMIP 6 data to find the relevant model which will better capture changes in the occurrence of wet and dry days (or spells) under different global warming levels (1.5 and 2°C) and different time horizons (near future and far future).

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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APPENDIX

Table 1. MK test results for different West African sub-domains.

Variable	p-Values			
	Western Sahel	**Central Sahel**	**Sudanian Zone**	**Guinea Coast**
P_W	**0.00005**	**0.00008**	0.9350	0.3822
P_D	**0.00005**	**0.00008**	0.9350	0.3822
P_{WW}	0.2041	0.6001	0.3822	0.6664
P_{WD}	0.2041	0.6001	0.3822	0.6664
P_{DD}	**0.00007**	**0.00000**	0.0747	0.2393
P_{DW}	**0.00007**	**0.00000**	0.0747	0.2393
P_{3W}	0.3453	0.5681	0.6664	1
P_{5W}	0.1880	0.8980	0.4773	0.6001
P_{7W}	0.0911	0.8067	0.2041	0.4629
P_{10W}	**0.0192**	0.8613	0.0747	0.3335
P_{3D}	**0.0231**	0.2998	0.0826	0.0747
P_{5D}	**0.0019**	**0.00001**	0.0546	0.3335
P_{7D}	**0.0019**	**0.00000**	0.0575	0.3453
P_{10D}	**0.0015**	**0.00000**	**0.0490**	0.3108

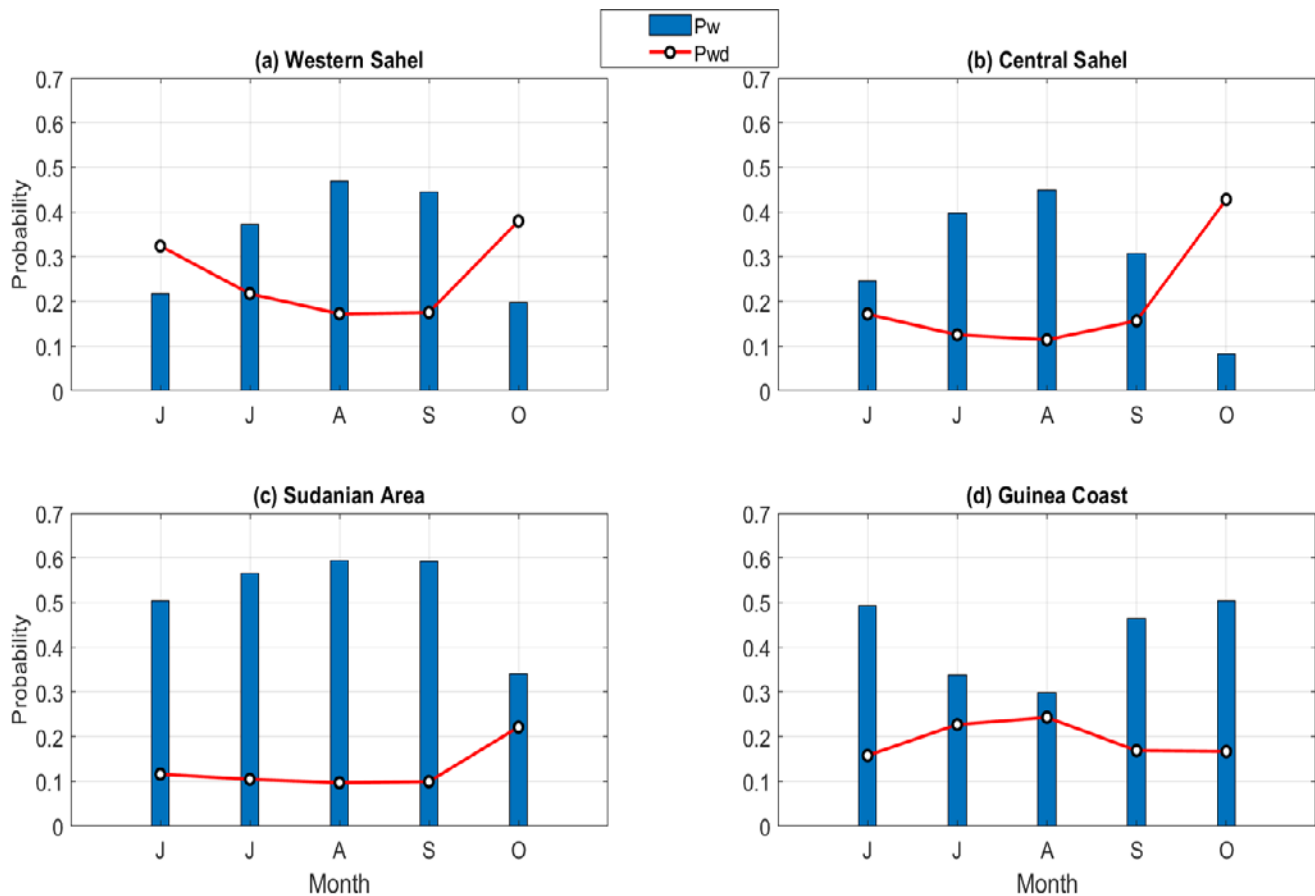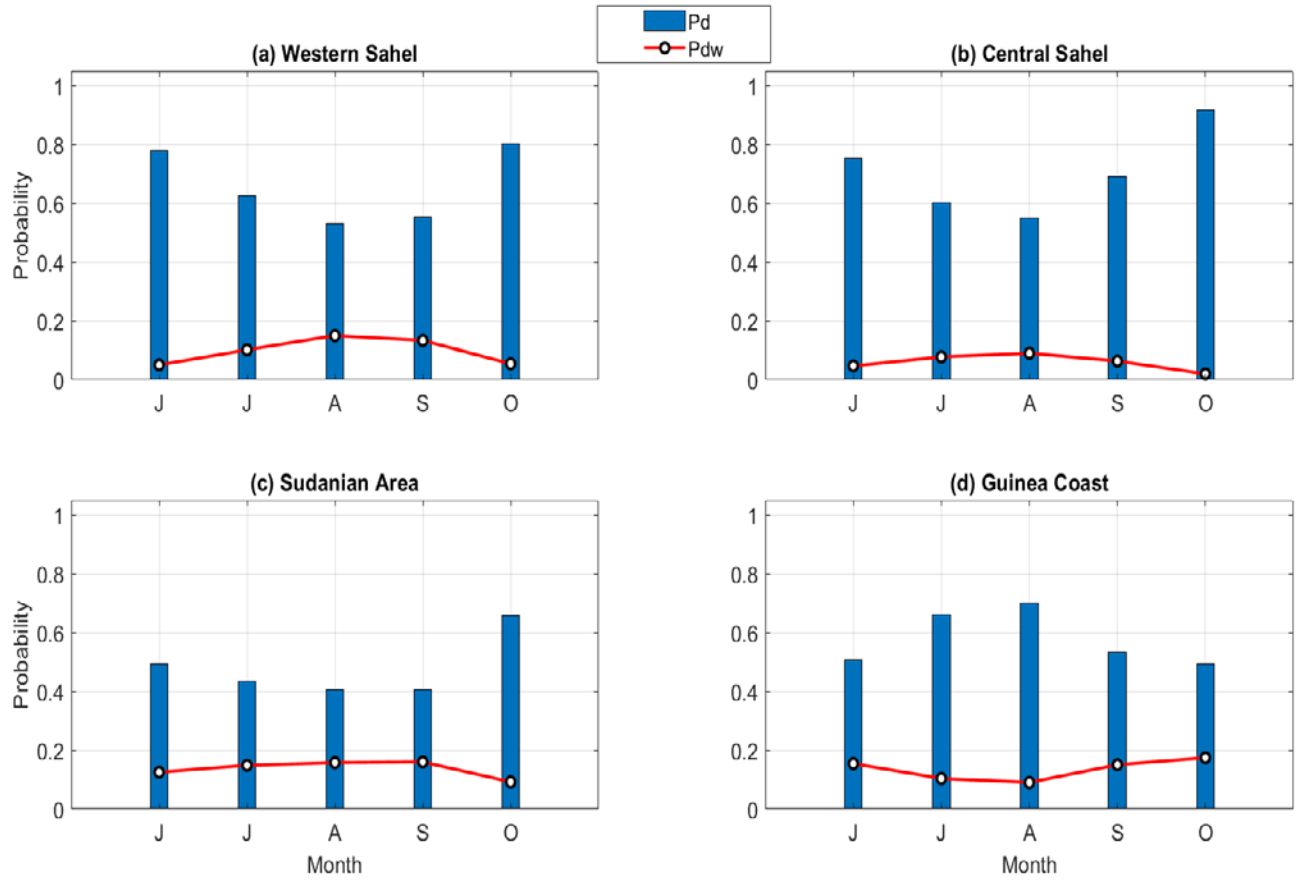Values in bold are statistically significant at the 95% confidence level.

Figure 1. Seasonal cycle of the transitional probabilities (curve; P_{WD}) and the probability of dry days (histogram; P_W) for the selected sub-domains.

Figure 2. Seasonal cycle of the transitional probabilities (curve; P_{DW}) and the probability of dry days (histogram; P_{D}) for the selected sub-domains.