CHARACTERISATION OF SAHELIAN WET AND DRY SPELLS UNDER RCP 4.5 AND 8.5 IN NIGERIA, WEST AFRICA

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ABSTRACT

The Sahelian region of Northern Nigeria is characterised by unreliable rainfall regime which is highly variable over different temporal scales. This variability is often evident spells of different durations which usually results in floods and droughts. Assessing how wet and dry spells will evolve in future climate is therefore crucial for addressing agricultural, water resources and environmental challenges. Using daily rainfall simulations from four Regional Climate Models (RCMs) provided by the Coordinated Regional Climate Downscaling Experiment (CORDEX), the future characteristics of wet and dry spells of different timescales were analysed based on two Representative Concentration Pathways (RCPs), 4.5 and 8.5, the wet and dry spells for the mid- and late –century. The characterisations were based on established categorisations. On the whole, the 2-3 days wet and dry spells are projected to be the most frequent, with the highest frequency of the 2-3 days (285 events) for the mid-century under RCP 4.5 expected at Maiduguri and the highest frequency (272 events) for 2-3 days dry spell for the late- century under RCP 8.5 expected at Sokoto. The >20 days wet spell and the >21 days dry spell are projected to be the least frequent with some locations not expected to experience the wet and dry spells of these duration categories. This portends reduced the risk of flood-induced crop failure and agricultural drought. The study recommends taking advantage of the expected suitable agro-climatic conditions to increase the acreage of land under cultivation and combat climate change induced challenges.

Keywords: African Easterly Waves, Late Century, Mid-Century, Rainfall, West African Monsoon

INTRODUCTION

In recent decades, the response of the West African summer monsoon rainfall to climate change has been a major focus of several studies such as Afiesimama et al. (2006), Sylla et al. (2010), Adeniyi (2016), Akinsanola et al. (2017), Akinsanola and Zhou (2018), Berthou et al. (2019) and Dosio et al. (2020). This response is manifested in the present-day variability of rainfall, which has the potential to affect water resource availability and management, as well as rain-fed agriculture, which is the mainstay of the region's economy. The changes witnessed in the West African monsoon have been attributed to changes in its features such as changes in the monsoon flow, the African Easterly Jet (AEJ), the African Easterly Wave (AEW), integrated moisture flux divergence and moisture static energy (Sylla et al., 2016).

A significant impact of changes to the West African monsoon is changes in the intra-seasonal variability of wet and dry spells. The duration and frequency of wet and dry spells are important determinants of water supply and demand on different spatial scales. In a country like Nigeria where agriculture is primarily rainfed, the occurrence and frequency of wet and dry spells of different durations have several implications. These range from reduced crop yield and higher risk of crop failure, food insecurity and higher probability of an increase in farmer-herder clashes due to pastoralists search for water and green pasture (Bako et al., 2020; Chimimba et al., 2023).

Furthermore, long-duration wet and dry spells have some socio-economic and environmental consequences. For example, prolonged dry spells could induce drought and eventual loss of farmers' income due to reduced harvest. Extremely long wet spells could result in flooding, risk of pathogens development, increase in water-borne diseases and release of pollutants into sources of water (Breinl et al., 2020).

In recognition of the importance of this crucial aspect of rainfall climatology, several studies have been conducted to analyse the characteristics of wet and dry spells in West Africa for both the present and future periods. These include a study by Froidurot and Diedhiou (2017), who characterised the wet and dry spell climatology of four sub-regions in West Africa for 17 years and discovered that the 2-3 days wet and dry and the isolated wet and dry days were the most numerous in the region. The analyses of changes in wet and dry spells by Bichet and Diedhiou (2018) showed that while there was an increase in the number of wet spells over the Sahelian region between 1981 and 2014, the average length showed a decline over the northern and eastern parts and an increase over the south-western part of the region. They also showed that while the number of dry spells during the period increased everywhere in the region, the southwestern part exhibited a slight decline.

The analyses of the frequency and distribution of wet and dry spells in Senegal by Fall et al. (2021), showed that wet spells generally exhibited greater spatial variability than dry spells, with the dry spell exhibiting a greater frequency of occurrence at the onset and cessation of rainy seasons in the study area. The characterisation of wet and dry spells over the Pra River catchment of Ghana by Osei et al. (2021) under three Representative Concentration Pathways (RCPs), 2.6, 4.5 and 8.5 shows an increase in both wet and dry spells during the future compared with the baseline period, and the lowest and highest frequency of spells expected under RCP 2.6 and 8.5 respectively (Osei et al., 2021)

For the present-day climate, many studies for example (Sawa & Adebayo 2012; Umar et al., 2020; Bako et al., 2020), have analysed the spatio-temporal variability of dry spells in northern Nigeria. However, there is a dearth of study that focuses on the occurrence of wet spells during the rainy season, as well as the expected future occurrences of wet and dry spells in the region. This study therefore assessed the expected future wet and dry spells characteristics of the rainy season in the Sahelian bioclimatic zone of Nigeria for the mid (2041-2070) and late (2071-2100) centuries under two contrasting climate change scenarios of RCP 4.5 and 8.5.

THE STUDY AREA

The Sahelian eco-climatic zone of Nigeria (represented by the meteorological stations in figure.1) is a semi-arid region located in the Northern part of the country. The region lies between Latitude 10^{o} N and 14^{o} N, and Longitude 3^{o} E and 15^{o} E. The region is subject to the influence of the tropical continental (cT) air mass which predominates in the dry season, between October and May, and the tropical maritime air mass (mT) which prevails in the rainy season between June and September (Adejuwon & Dada, 2021).

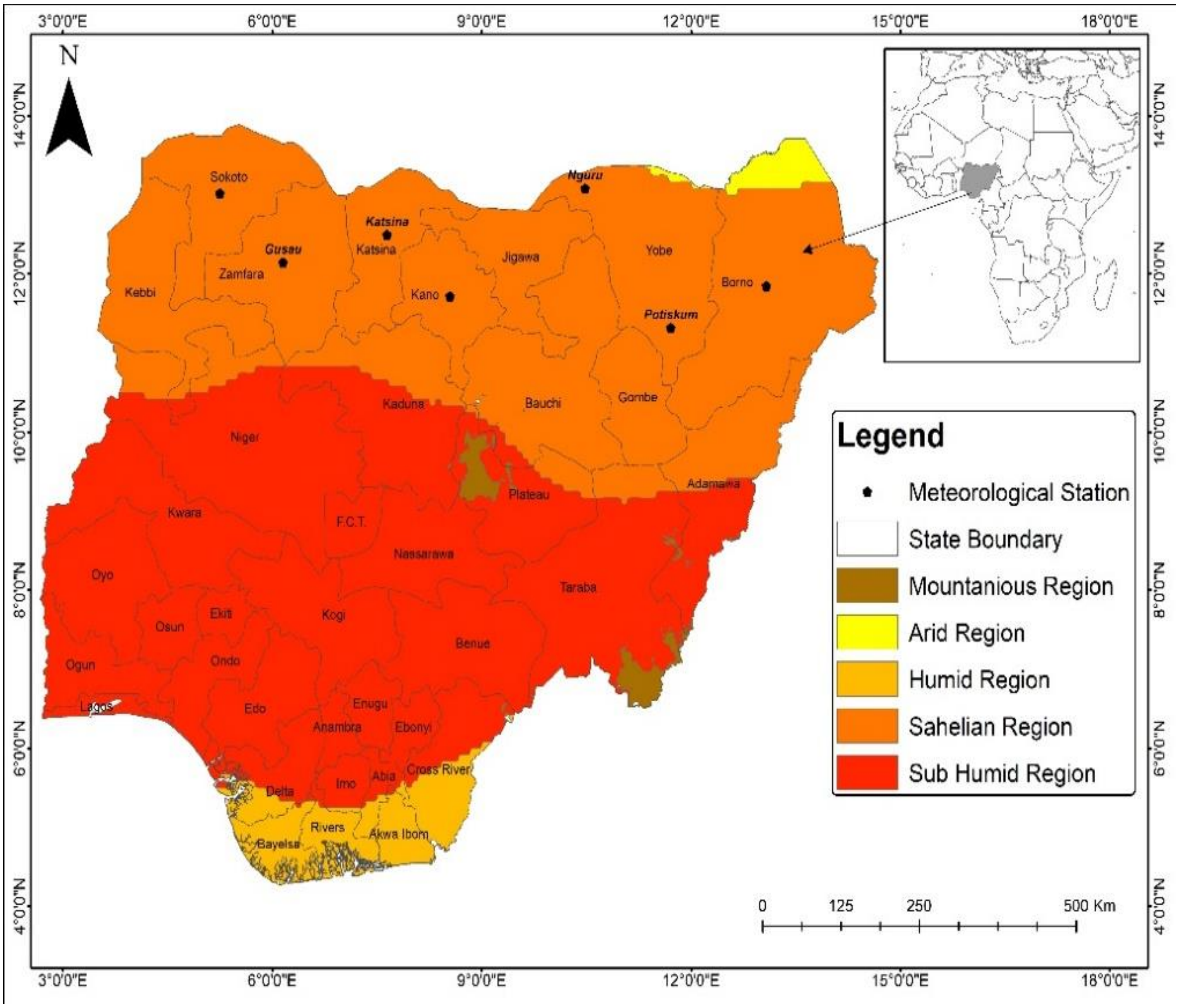

Figure 1: The Study Area

Rainfall in the area is subject to deep convective systems in the form of squall lines and thunderstorms as is obtainable in the West African Sahel (Omotosho, 2008). Annual rainfall distribution in the zone varied between 480 and 1,000mm, 580 and 1,000mm, and 500 and 920mm for the periods, 1910 to 1939, 1940 to 1969, and 1970 to 1999 respectively (Ogungbenro & Morakinyo, 2014). The diurnal temperature range is consistent with the rest of northern Nigeria. Daily maximum temperature can rise as high as 45^{o} C during the high sun season, and fall as low as 12^{o} C during the dry Harmattan season (Shiru et al., 2019). The vegetal cover of the area is predominantly sparse and mostly made up of short bushes and low growing shrubs such as Wattles (*Acacia Spp*), African Birch (*Anogeisus leiocarpus*), Desert Date (*Balanites aegyptiaca*), Myrrh (*Commiphora quadricincta*), Grey-Leaved Saucer Berry (*Cordia rothii*), and the Toothbrush Tree (*Salvadora persica*) (Nigeria Environmental Study Action Team [NEST], 1991).

MATERIALS AND METHODS

Model Data

Daily rainfall simulations driven by four Coupled Model Inter-comparison Project Phase 5 (CMIP5) Global Climate Models (GCMs) downscaled by the Rosby Centre Regional Climate Model (RCA4) developed by Sveriges Meteorologiska och Hydrologiska Institut (SMHI), Sweden, under the Coordinated Regional Climate Downscaling Experiment (CORDEX) Africa Project was used for this study. These were downloaded at https://esg-dn1.nsc.liu.se/search/cordex/. Two future scenarios based on Representative Concentration Pathways (RCP) 4.5 and 8.5 were considered for the mid-century (2041-2070) and the late-century (2071 – 2100).

RCP 4.5 represents a pathway that reaches a stabilisation of 4.5W/m^2 by 2100 without exceeding the value while RCP 8.5 implies an increasing radiative pathway approaching 8.5W/m^2 by 2100 (Van. Vuuren et al., 2011; Thomson, et al., 2011). Both RCPs were selected to assess if there will be marked or significant differences in the characteristics of wet and dry spells, as well as isolated wet and dry days under conditions of medium-low stabilisation pathway represented by RCP 4.5 and conditions of unmitigated greenhouse emissions implied by RCP 8.5. The CMIP5 models used for the study are CanESM2, CNRM-CM5, IPSL-CM5A-MR and MPI-ESM-LR. The models were used due to their relative ability in simulating aspects of West Africa's rainfall as shown by studies such as those of Akinsanola et al. (2017) and Dosio et al. (2019). The characteristics of the models are as presented in Table 1.

Table 1: Characteristics of the Models used for the Study

Modelling Institution	RCM	Driving GCM	Short Name	Ensemble
Sveriges Meteorologiska och Hydrologiska Institut (SMHI), Sweden,	SMHI Rosby Centre Regional Atmospheric Model (RCA4)	CCma-CanESM2	CanESM2	r1i1p1
		CNRM-CERFACS-CNRM-CM5	CNRM-CM5	r1i1p1
		IPSL-CM5A-MR	IPSL-CM5A-MR	r1i1p1
		MPI-M-MPI-ESM-LR	MPI-ESM-LR	r1i1p1

Institutions: CCma - Canadian Centre for Climate Modelling and Analysis; CNRM - Centre National de Recherches Météorologiques; IPSL - Institut Pierre-Simon Laplace; MPI-M- Max Planck Institute for Meteorology. **Ensemble r1i1p1**- r refers to realisation, i means initialisation method, p refers to physics

The downloaded model data are for seven meteorological stations within the study area. Further information on the meteorological stations used in this study is as shown in Table 2. These were selected due to their long term existence in the Sahelian eco-climatic zone.

Table 2: Characteristics of Meteorological Stations used in the Study

S/N	Station Name	WMO ID	Latitude (º N)	Longitude (º E)	Elevation (m)
1.	Gusau	65015	12.17	6.70	463.9
2.	Kano	65046	12.05	8.20	472.5
3.	Katsina	65028	13.02	7.68	517.6
4.	Maiduguri	65082	11.85	13.08	353.8
5.	Nguru	65064	12.88	10.47	343.1
6.	Potiskum	65073	11.70	11.03	414.8
7.	Sokoto	65010	13.02	5.25	350.8

Data Analysis

Wet and dry spells of different durations and isolated wet and dry days for the rainy season of the Sahelian ecological zone (June to September) were analysed for the future and baseline periods. A threshold of 1mm/day was used to distinguish a wet or dry day, based on earlier studies by Froidurot and Diedhiou (2017), Ayar and Mailhot (2021), Fall et al., (2021) and Osei et al., (2021). A dry day is defined as one whose cumulative rainfall is less than 1mm, while a wet day is one whose rainfall amount is greater than or equal to 1mm (Basse et al., 2021).

Wet spells are sequences of consecutive wet days preceded and followed by dry days, while dry spells are sequences of dry days preceded and followed by wet days. An isolated wet day is surrounded by two dry days while an isolated dry day is that, which is surrounded by two wet days. (Froidurot & Diedhiou, 2017). The wet and dry spells were analysed based on similar categorisation by used by Froidurot and Diedhou (2017), and Osei et al., (2021). The wet spells were analysed for 2-3 days, 4-5 days, and 6-9 days which is associated with the African Easterly Waves (AEWs), as well as the 10-20 day wet spells which is associated with the African monsoon rainfall (Froidurot & Diedhou 2017), while the analysis of dry spells was based on 2-3 days, 4-6 days, 7-15 days, and 16-21days.

RESULTS AND DISCUSSION

Projected Future Wet Spells

The projected future wet spell of different duration categories, 2-3 days, 4-5 days, 6-9 days, 10-20 days and >20 days from the 4 RCMs for the mid and late century under RCP 4.5 and 8.5 are as presented in Tables 3 to 6.

Table 3: Wet Spell in the Mid-Century under RCP 4.5

	CanESM2					CNRM-CM5				
Station	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days
Gusau	118	45	56	38	10	94	65	63	78	16
Kano	77	52	48	40	16	107	64	92	57	19
Katsina	110	48	51	42	5	130	64	80	66	11
Maiduguri	148	58	35	20	2	265	111	66	14	0
Nguru	145	64	42	25	0	200	97	83	27	2
Potiskum	104	60	55	29	11	154	90	77	63	9
Sokoto	218	66	35	17	3	220	94	69	35	2
	IPSL-CM5A-MR					MPI-ESM-LR				
Station	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days
Gusau	125	70	51	38	5	138	86	77	66	9
Kano	115	61	58	24	3	153	93	65	61	6
Katsina	125	44	37	37	7	184	62	73	43	4
Maiduguri	203	71	22	22	0	285	93	46	11	0
Nguru	143	51	25	25	0	204	77	52	22	1
Potiskum	149	65	56	56	1	204	97	94	33	5
Sokoto	194	84	37	37	1	378	95	65	24	0

Table 4: Wet Spell in the Late Century under RCP 4.5

	CanESM2					CNRM-CM5				
Station	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days
Gusau	112	49	46	41	11	117	66	70	64	18
Kano	75	41	39	33	18	125	64	66	61	19
Katsina	123	48	51	34	6	145	74	87	57	3
Maiduguri	150	53	35	21	0	275	104	39	21	0
Nguru	139	57	41	21	1	209	84	71	23	1
Potiskum	122	62	44	35	5	175	82	91	50	9
Sokoto	197	63	43	18	0	220	107	84	31	1
	IPSL-CM5A-MR					MPI-ESM-LR				
Station	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days
Gusau	133	56	61	28	5	165	75	86	62	9
Kano	126	64	66	38	1	164	70	79	55	12
Katsina	128	61	34	16	1	194	85	60	41	5
Maiduguri	180	53	19	2	0	266	72	47	17	0
Nguru	147	49	18	4	0	214	66	55	23	0
Potiskum	151	64	36	18	1	197	96	83	40	2
Sokoto	181	61	34	8	0	267	107	66	19	1

Table 5: Wet Spell in the Mid-Century under RCP 8.5

	CanESM2					CNRM-CM5				
Station	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days
Gusau	105	46	42	48	14	111	72	73	81	14
Kano	68	42	54	36	19	110	75	88	72	10
Katsina	135	44	57	33	7	133	86	84	61	7
Maiduguri	183	53	43	22	0	257	94	68	14	0
Nguru	163	74	36	24	2	213	92	76	27	0
Potiskum	150	67	53	33	8	175	92	103	43	5
Sokoto	225	80	38	19	2	243		86	39	0
	IPSL-CM5A-MR					**MPI-ESM-LR**				
Station	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days
Gusau	150	75	44	41	3	161	106	78	60	9
Kano	134	68	56	29	2	157	73	103	68	5
Katsina	117	43	49	22	3	170	102	78	60	1
Maiduguri	213	57	15	5	0	259	96	50	14	0
Nguru	148	56	34	8	0	225	78	81	18	0
Potiskum	172	74	55	18	0	211	147	79	40	2
Sokoto	213	74	49	8	0	271	108	61	28	0

Table 6: Wet Spell in the Late Century under RCP 8.5

	CanESM2					CNRM-CM5				
Station	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days
Gusau	98	60	37	34	12	161	75	65	70	11
Kano	88	46	52	38	13	157	92	79	68	10
Katsina	116	64	50	42	3	173	99	89	52	6
Maiduguri	166	53	44	18	1	282	79	71	16	0
Nguru	193	62	40	18	1	263	90	65	18	1
Potiskum	139	62	57	31	3	183	91	90	55	3
Sokoto	190	69	38	22	1	235	108	66	39	2
	IPSL-CM5A-MR					**MPI-ESM-LR**				
Station	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days	2-3 Days	4-5 Days	6-9 Days	10-20 Days	> 20 Days
Gusau	121	75	58	30	10	202	89	82	59	2
Kano	138	61	36	30	10	193	98	93	40	9
Katsina	133	72	41	22	3	221	110	80	32	0
Maiduguri	185	58	39	7	0	296	81	42	6	0
Nguru	164	54	38	8	0	246	95	45	10	0
Potiskum	148	77	57	21	1	248	107	94	28	0
Sokoto	237	67	28	11	0	320	116	56	8	0

As shown in Tables 3 to 6, the 2-3 days wet spells are projected to be the most predominant across all the models under both RCPs in the mid and late century. As can be deduced from the Tables, higher frequencies of the 2-3 days wet spells are projected by MPI-ESM-LR relative to the other models (Figure.2).

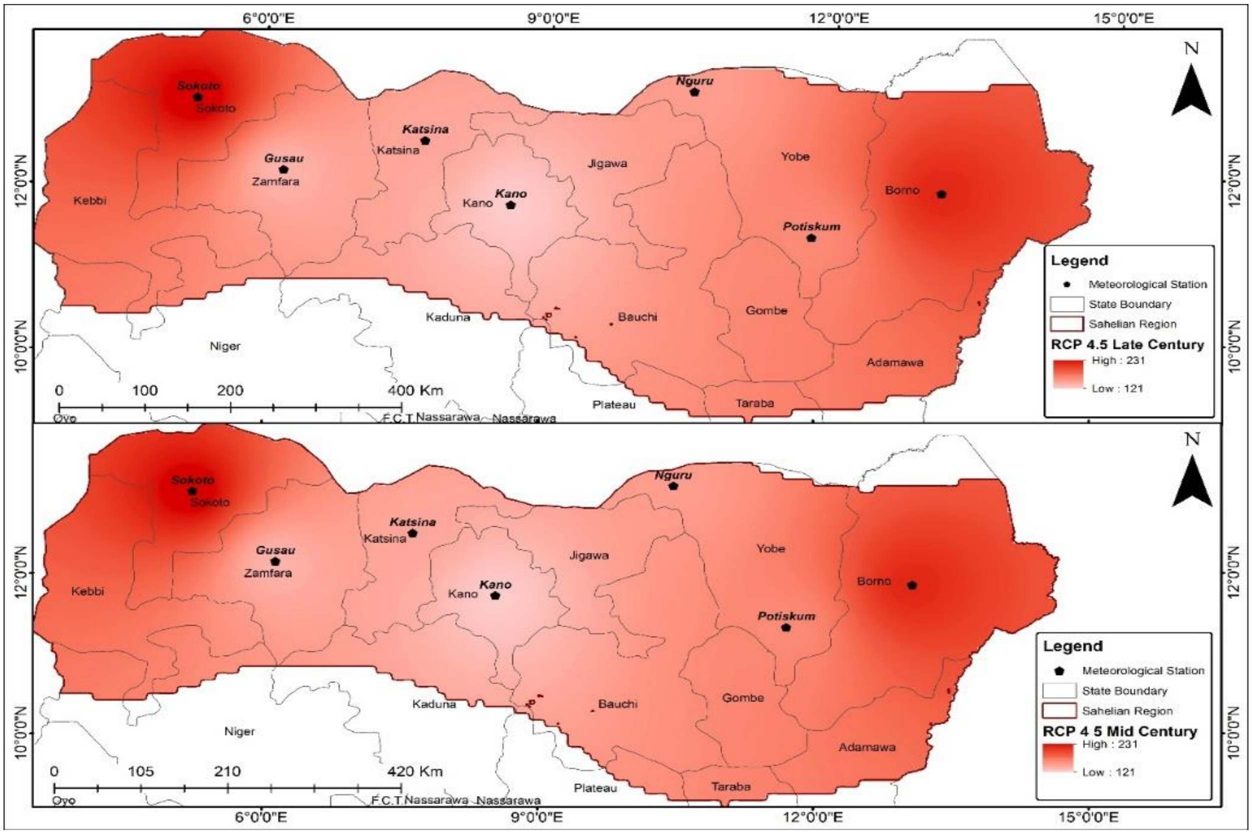

Figure 2: Frequency of occurrence of the 2-3 days wet spell for the mid and late century under RCP 8.5 based on MPI-ESM-LR

In comparison to the 2-3 days wet spells, the 4-5 days wet spell, the 6-9 days and the 10-20 days wet spells are projected to be relatively fewer. For the 4-5 days wet spells, a maximum of 111 events is projected to be experienced at Maiduguri during the mid-century under RCP 4.5 while a maximum of 147 events is projected to be experienced at Potiskum under RCP 8.5 also during the mid-century. For the 6-9 days and 10-20 days wet spell, the projected frequencies for the mid and late century for both RCPs are expected to be less than 105 events. The least frequent spells as shown in Tables 3 to 6 are the > 20 days wet spell, with a maximum of 19 events projected for the study periods at Kano based on CNRM-CM5.

The predominance of the 2-3 days wet spell and the relatively high frequency of the 4-5 days wet spell are indications that they are expected to be major contributors to the seasonal rainy days in the mid- and late-century under both RCP 4.5 and 8.5. These high frequencies are also in line with the high level of recurrence of the 3-5 days regime of the AEWs as established in a study by Diedhiou et al. (1998).

The AEWs are westward moving synoptic scale disturbances over Africa and the Atlantic linked with daily rainfall during the boreal or Northern Hemisphere summer. AEWs originate upstream of the Sudanese highlands in Northeast Africa and spread across West Africa around the mid-tropospheric Africa Easterly Jet (AEJ) through combined baroclinic and barotropic conversion. They are detectable at 600 to 700 hpa on both sides of the AEJ and are very important for synoptic-scale rainfall variability over the Sahelian region, regulating rainfall through the initiation and organisation of Mesoscale Convective Systems (MCSs) and squall lines during the monsoon season between June and September.

The AEWs are of two types: the 3-5 days AEWs which have an average wavelength of between 3,000 and 5,000km north and south of the AEJ, and the 6-9 days AEWs, which have wavelengths in the range of 5,000 to 6,000km and are found north of the AEJ. (Skinner & Diffenbaugh, 2013; Basse et al., 2021; Enyew & Mekonnen, 2022; Raj et al., 2023; Diedhiou et al., 1999). The 6-9 days AEWs are characteristically more intense in August and September during the second half of the monsoon (Wu et al., 2013).

The projected high frequencies of short-duration wet spells, especially the prevalence of the 2-3 days wet spells are generally beneficial for agriculture, especially at the onset of the planting season, due to increased potential soil moisture replenishment and the provision of adequate green water to support crop growth and ensure food security in the region. A greater probability of waterlogging of farms and cultivated crops exist during periods of projected long duration wet spells such as the 6-9 days and 10-20 days wet spells.

Waterlogging has a myriad of implications for soil properties and plant growth. For soil properties, the effects include changes in physical properties such as soil compaction, increased bulk density, structural changes, oxygen depletion leading to hypoxic or anoxic soil environments, carbon-dioxide accumulation, and reduced diffusion coefficient for gases. Changes in soil chemical properties range from ion toxicity to secondary metabolic toxicity. Changes in electro-chemical properties of soil could result in increase in specific conductance, decrease in redox potential and decrease in soil pH while changes in biological characteristics could result in reduced mineralisation, decrease in aerobic microbial activity and reduced immobilisation (Manik et al., 2019).

With respect to plant growth, waterlogging could result in reduced photosynthetic activity and reduced stomata conductance by leaves, enhanced starch degradation, reduction in soluble carbohydrates and Adenosine-5'-Triphosphate (ATP) in cotyledons and hypocotyls, reduced biosynthesis and enhanced degradation of chlorophyll. Others include reduction in root hydraulic conductivity, increased root damage and restriction of root growth, reduction in water uptake, decrease in biological nitrogen fixation, and reduction in plant growth and yield (Manix et al., 2019; Kaur et al., 2020).

Projected Future Dry Spells

Tables 7 to 10 show the frequencies of dry spells of different categories for the mid and late centuries under RCPs 4.5 and 8.5.

Table 7: Dry Spell in the Mid-Century under RCP 4.5

	CanESM2					**CNRM-CM5**				
Station	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days
Gusau	87	20	12	0	0	89	17	4	0	0
Kano	71	16	6	0	0	110	23	15	0	0
Katsina	95	18	5	0	0	103	30	15	0	1
Maiduguri	137	36	22	0	1	205	67	14	2	0
Nguru	100	31	23	0	0	155	53	26	0	3
Potiskum	92	32	5	1	0	130	23	10	0	0
Sokoto	146	43	11	1	0	186	39	10	0	0
	IPSL-CM5A-MR					**MPI-ESM-LR**				
Station	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days
Gusau	121	37	19	5	3	134	34	8	0	0
Kano	86	45	25	10	1	121	41	23	1	0
Katsina	78	34	24	7	3	142	53	26	3	1
Maiduguri	160	69	44	8	0	214	62	43	2	0
Nguru	106	42	34	10	5	147	70	43	4	3
Potiskum	123	51	38	3	2	158	47	21	2	1
Sokoto	168	49	29	2	4	231	74	17	0	0

Table 8: Dry Spell in the Late Century under RCP 4.5

	CanESM2					**CNRM-CM5**				
Station	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days
Gusau	100	18	11	0	0	99	20	7	0	0
Kano	78	13	7	0	0	99	24	14	0	0
Katsina	78	23	8	0	0	102	47	20	2	0
Maiduguri	107	33	17	0	1	216	56	31	3	0
Nguru	98	32	16	0	0	139	52	37	3	5
Potiskum	103	22	12	0	0	125	34	19	0	0
Sokoto	151	46	8	0	0	179	47	12	0	0
	IPSL-CM5A-MR					**MPI-ESM-LR**				
Station	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days
Gusau	100	35	9	3	0	137	42	7	0	1
Kano	91	31	22	4	0	130	48	17	0	1
Katsina	91	39	29	5	0	156	51	29	3	1
Maiduguri	135	90	37	0	0	210	96	30	4	1
Nguru	103	41	37	4	2	140	91	40	10	1
Potiskum	117	49	31	5	0	168	61	22	2	1
Sokoto	146	43	21	2	1	224	67	20	1	1

Table 9: Dry Spell in the Mid-Century under RCP 8.5

	CanESM2					**CNRM-CM5**				
Station	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days
Gusau	82	36	11	0	0	112	17	2	0	1
Kano	67	21	6	0	0	95	30	7	0	1
Katsina	89	24	9	0	0	114	32	17	0	0
Maiduguri	137	43	18	2	2	235	64	21	1	1
Nguru	120	24	16	0	1	188	49	24	5	2
Potiskum	86	29	13	0	0	138	31	7	1	1
Sokoto	184	38	12	0	0	224	52	7	0	0
	IPSL-CM5A-MR					**MPI-ESM-LR**				
Station	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days
Gusau	109	40	15	1	0	153	19	9	0	0
Kano	90	40	20	5	0	127	34	9	0	0
Katsina	76	36	29	2	2	161	38	16	1	0
Maiduguri	151	66	40	2	5	215	64	33	3	0
Nguru	110	37	40	7	3	187	86	27	3	0
Potiskum	110	46	34	3	0	165	45	11	3	0
Sokoto	178	45	20	1	1	233	72	11	0	0

Table 10: Dry Spell in the Late Century under RCP 8.5

	CanESM2					**CNRM-CM5**				
Station	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days
Gusau	88	26	7	0	0	106	18	1	0	0
Kano	86	17	2	1	0	115	17	7	0	0
Katsina	95	22	7	0	0	135	33	13	0	0
Maiduguri	165	32	14	1	1	202	59	26	1	0
Nguru	156	26	6	0	0	214	44	19	3	0
Potiskum	97	23	7	0	0	170	37	5	1	0
Sokoto	184	43	8	1	0	201	47	13	0	0
	IPSL-CM5A-MR					**MPI-ESM-LR**				
Station	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days	2-3 Days	4-6 Days	7-15 Days	16-21 Days	> 21 Days
Gusau	93	40	13	2	0	174	25	8	0	0
Kano	82	29	22	5	2	187	38	14	0	0
Katsina	92	40	19	5	1	170	52	21	1	0
Maiduguri	145	62	38	1	2	227	96	40	0	1
Nguru	95	45	44	6	1	180	73	40	3	2
Potiskum	124	71	24	2	2	174	116	19	0	0
Sokoto	183	53	24	2	0	272	62	13	1	0

Similar to what is projected for the wet spell, the 2-3 days dry spell is expected to be the most frequent occurrence under both RCPs for the study periods. As shown in Table 10, a maximum of 272 events is expected at Sokoto based on MPI-ESM-LR for the study periods under both

RCPs. In comparison with the 2-3 days dry spell, the 4-6 days and the 7-15 days dry spells are projected to be significantly lesser, the projected maximum number of the 4-6 days dry spell expected to be less than 100 events and the 7-15 days dry spell expected to be less than 45 events. Figure 3 shows the frequency of occurrence of the 2-3 days dry spell for the mid and late century under RCP 4.5 based on MPI-ESM-LR.

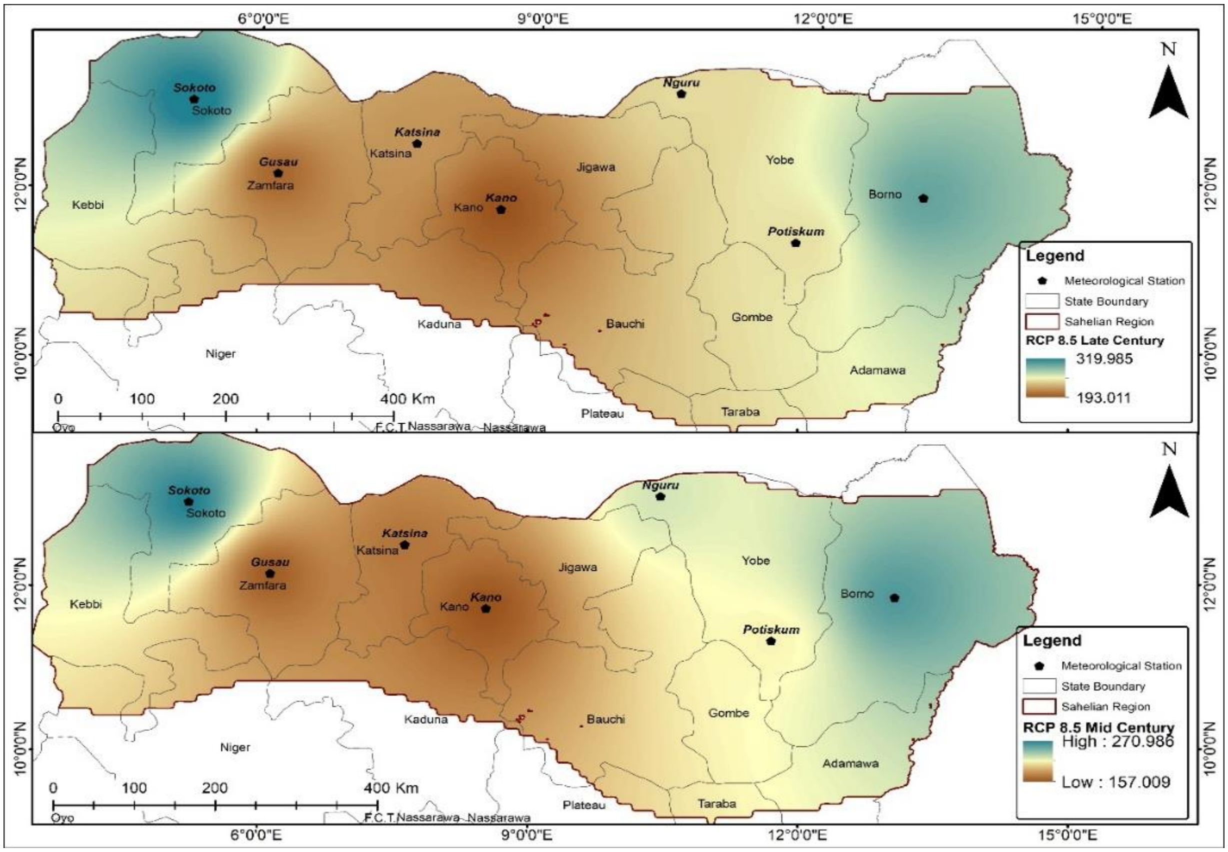

Figure. 3: Frequency of occurrence of the 2-3 days dry spell for the mid and late century under RCP 4.5 based on MPI-ESM-LR

The projected preponderance of the 2-3 days dry spell in the study area is in line with the findings of Ibrahim et al. (2012) who analysed different characteristics of the rainy season and found that short duration dry spells (< 5 days) are projected to be the most frequent by the RCMs for Burkina-Faso, a country located in the Central Sahelian part of West Africa. What this suggests is the future period is expected to experience fewer occurrences of protracted droughts and water deficit, reducing the need for supplemental irrigation during the farming season. Agricultural losses are tends to be minimised when the short duration dry spells, such as the 2-3 days dry spell are interspersed with short duration wet spell, such as the 2-3 days wet spell, as sufficient time is available for the rains to infiltrate and percolate into the root zone of the plants.

Furthermore, it can be observed from the results that the longer the dry spell duration, the lesser the frequency of occurrence, especially with regards to the 16-21 days and >21 days dry spells. The very few occurrences of the 16-21 days dry spell projected by the models is consistent with the findings of Froidurut and Diedhiou (2017) which showed that the Sahel is typically characterised by an average of one dry spell of 16-21 days duration. The lesser occurrences of the16-21 days and >21 days dry spells implies that there will be fewer episodes of extreme drought during the wet seasons of the mid- and late centuries under both scenarios. Dry spells in the Sahel are influenced by various atmospheric circulation patterns, namely, a weak monsoon flow, a southward displacement and strengthening of the African easterly jet (AEJ), a weakening of the Tropical easterly jet (TEJ), a decline of the deep core of ascent between the AEJ and TEJ, a decrease in relative humidity and reduced AEWs' activities (Sylla, et al., 2010; Basse et al., 2021).

Projected Future Isolated Wet and Dry Days

The projected isolated wet and dry days is as shown in Tables 11 to 14.

Table 11: Isolated Wet Days in the Mid and Late Century under RCP 4.5

	Mid-Century				Late Century			
Station	**CanESM2**	**CNRM-CM5**	**IPSL-CM5A-MR**	**MPI-ESM-LR**	**CanESM2**	**CNRM-CM5**	**IPSL-CM5A-MR**	**MPI-ESM-LR**
Gusau	78	69	110	122	91	86	115	124
Kano	63	71	125	129	62	87	129	118
Katsina	114	90	111	161	75	114	119	174
Maiduguri	198	280	235	295	168	277	248	299
Nguru	153	187	157	227	129	201	166	202
Potiskum	80	114	135	134	82	124	149	121
Sokoto	193	195	171	207	146	191	168	218

Table 12: Isolated Wet Days in the Mid and Late Century under RCP 8.5

	Mid-Century				Late Century			
Station	**CanESM2**	**CNRM-CM5**	**IPSL-CM5A-MR**	**MPI-ESM-LR**	**CanESM2**	**CNRM-CM5**	**IPSL-CM5A-MR**	**MPI-ESM-LR**
Gusau	98	70	127	112	84	94	115	150
Kano	70	102	132	98	79	99	109	163
Katsina	113	110	134	170	102	126	157	192
Maiduguri	203	271	287	293	194	317	243	311
Nguru	145	234	155	238	176	236	178	253
Potiskum	92	118	139	148	111	138	159	166
Sokoto	166	183	156	194	164	205	212	258

Table 13: Isolated Dry Days in the Mid and Late Century under RCP 4.5

	Mid-Century				Late Century			
Station	**CanESM2**	**CNRM-CM5**	**IPSL-CM5A-MR**	**MPI-ESM-LR**	**CanESM2**	**CNRM-CM5**	**IPSL-CM5A-MR**	**MPI-ESM-LR**
Gusau	220	274	200	323	210	306	235	339
Kano	181	302	223	317	155	274	220	295
Katsina	206	300	178	308	207	318	162	307
Maiduguri	239	442	231	400	232	422	216	355
Nguru	218	355	161	249	220	335	165	275
Potiskum	201	336	193	332	206	354	196	290
Sokoto	293	395	218	353	246	405	210	360

Table 14: Isolated Dry Days in the Mid and Late Century under RCP 8.5

	Mid-Century				Late Century			
Station	**CanESM2**	**CNRM-CM5**	**IPSL-CM5A-MR**	**MPI-ESM-LR**	**CanESM2**	**CNRM-CM5**	**IPSL-CM5A-MR**	**MPI-ESM-LR**
Gusau	206	294	252	353	194	355	240	338
Kano	186	329	234	337	204	351	223	355
Katsina	249	324	201	355	234	370	239	377
Maiduguri	279	361	209	396	254	424	264	359
Nguru	257	372	176	322	281	395	222	331
Potiskum	264	372	236	382	268	375	256	385
Sokoto	252	365	229	359	228	395	280	393

Under RCP 4.5, a maximum of 295 and 299 isolated wet days are expected at Maiduguri during the mid-century and the late century respectively, based on MPI-ESM-LR projections. Under RCP 8.5, the maximum frequency of isolated wet days are projected to be experienced at Maiduguri, with a maximum of 293 days and 311 days expected during the mid and late century according to the projections by MPI-ESM-LR. The maximum number of isolated dry days are also projected to be experienced at Maiduguri under both RCPs and study periods. Under RCP 4.5, a maximum of 442 and 422 days are expected during the mid and late century respectively according to CNRM-CM5. Under RCP 8.5, a maximum of 396 days are expected during the mid-century and a maximum of 421 days are expected during the late century based on MPI-ESM-LR and CNRM-CM5 respectively.

The generally high numbers of isolated wet and dry days expected in the study area, suggests that they will not only play a significant role in the duration of the rainy season but also in the determination of the water balance and availability of water resources for different uses in the region.

CONCLUSION

Knowledge of the expected future variability in the characteristics of wet and dry spells in the Sahelian eco-climatic region of Nigeria is important for its predominantly rain-fed crop production system and the sustainable management of water resources. For many decades, the region has remained highly vulnerable to the perturbations and vagaries of weather and climate, which have negatively impacted livestock production and food security and have sometimes resulted in ecological crises and social conflicts such as farmer-herder clashes.

From the results of the study, it can be concluded that that the short duration (2-3 days) wet and dry spells are expected to be the most frequent, while conversely, the longer duration wet and dry spells (>20 days wet spell, 16-21 days dry spell, and >21 days dry spell) are expected to be the least frequent.

During periods of expected longer duration wet spells, it is recommended that measures such as the cultivation of flood-tolerant crop varieties, raised bed farming systems, and subsurface tile drainage can be adopted as crop management and adaptive water management strategies.

The expected fewer occurrences of the longer-duration dry spell imply fewer episodes of hydrological drought and greater availability of surface and sub-surface water to meet the study area's agricultural, socio-economic, and ecological needs. With the likelihood of a reduced risk of flood-induced crop failure, policies geared towards increasing the acreage of farmlands under cultivation should be implemented to take advantage of the expected suitable agro-climatic conditions in the study area. More importantly, an innovative Adaptation Benefits Measurement (ABM) that strengthens the benefits accruing from the predominance of the shorter-duration (2-3 days) wet spell and fewer occurrences of the longer-duration dry spell needs to be implemented.

A deliberate policy implementation of multiple multi-purpose reservoirs to conserve water for year-round supply, afforestation and other uses in the face of challenging climate change issues is highly recommended. These should be small to medium-sized multi-purpose reservoirs spread across the region with excellent spatial efficiency. The policy should be integrated with a coherent approach to unify the sub-regional governments for the mutual benefit of the common opportunity provided by the biophysical system of the region. Insights into the future variability of wet and dry spells could serve as a basis for informed decision-making in the agricultural and other sectors. Also, it provides necessary information for designing appropriate early warning systems and hydro-agricultural infrastructures. Such information could aid farmers in irrigation scheduling and assist decision-makers in developing an integrated water resources management plan for the region.

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