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DIURNAL CIRCLE OF THE WEST AND CENTRAL AFRICAN MONSOON: PROFILES OF WIND AND MOISTURE FLUX DURING MAM SEASON

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ABSTRACT

*This research work analyzed the diurnal circle of wind profiles and moisture fluxes in seven zones of West and Central Africa during March – April – May (MAM). Results were achieved by analyzing diurnal variability of monsoon flow (wind and moisture fluxes) inland using the European Centre for Medium-range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) zonal and meridional wind profiles. The three rainforest zones (West-Coast, Dry and Nigeria-Cameroon rainforest) indicated the presence of African Easterly Jet (AEJ) between 650mb and 700mb, subtropical westerly jet (stronger in the Sudano and Sahel than in the rainforest and savannah) close to 200mb, and a Nocturnal Low-Level Jet (NLLJ) close to the surface. The moisture fluxes were found to be stronger in the dry rainforest zone, reaching up to 100 (g/kg*m/s), than for all the other zones. The southwesterly influx of moisture, which penetrates only into the rainforest and savannah zones, is always at its peak during the night and morning hours. This often resulted in more frequent monsoonal or stratiform precipitation during the morning hours (6Z) than other diurnals (0Z, 12Z, and 18Z). The surface moisture is consistently transported into four zones (the three rainforests and the Nigeria Savannah) south of 12oN during the MAM season, particularly during the night (0Z) and morning (6Z) hours. Peak values of moisture transport into these four zones were in the range of 100 – 160 kg m-1 s-1. Vertically integrated (1000 – 850mb) moisture flux convergence, is observed to be consistent along the Nigeria/Cameroon west-coast rainforest during the night (0Z) and morning (6Z) periods, and in the eastern axis of Central Africa and South Sudan (CASS) Savannah during the morning (6Z) and day (12Z) periods. The presence of high moisture at lower levels in the West African sub-region contributes significantly to high rainfall amounts and may cause significant flooding during the rainfall season.*

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1.0 INTRODUCTION

Past research regarding the West African Monsoon (WAM) mainly focused on two major areas: large-scale dynamics such as inter-annual and decadal variability in the monsoon (Rowell, 2001; Janicot*et al.*, 2001) and finer scales interactions such as the formation of AEW and MCSs (Diedhiou *et al.*, 1999 and Mathon and Laurent, 2001). The diurnal variability of the WAM has been largely overlooked, partly due to the scarcity of high-frequency observations in West Africa. The African Monsoon

Multidisciplinary Analysis (AMMA, Redelsperger *et al*., 2006) observational field campaign, which occurred in 2006, has greatly improved the spatial and temporal resolution of observations available over West Africa. These AMMA field observations allow researchers to assess the dynamic, thermodynamic and mesoscale processes that control the diurnal cycle of convective systems in the WAM.

Near the Guinea Coast of tropical West Africa, deep convective systems during the monsoon season have been shown to develop in the late afternoon and often reach a maximum in the evening (Balogun *et al*., 2022a). In sub-Saharan Africa, the diurnal cycle of convection has been found to correspond with boundary layer destabilization caused by daytime heating and surface energy fluxes (Yang and Slingo, 2001). In the semi-arid regions of the Sahel however, convection has been shown to develop in the evening, with peak intensity occurring in the early morning hours (Nesbitt and Zipser, 2003; Mohr, 2004). Cool pools are known to be an integral part of MCSs for their sustenance and secondary development of new convective cells (Provod*et al*. 2016;Balogun *et al*. 2022b). The diurnal cycle of convective systems in the Sahel has in large part been explained by the westward propagation of MCSs throughout the Sahel region (Balogun *et al*., 2023**)**. In West Africa, MCSs are often triggered by elevated daytime heating and orography (Rowell and Milford, 1993; Balogun *et al*., 2023). These storms often migrate westward away from their origins, such that the timing of peak rainfall occurs much later as the MCS migrate farther away from its origin (Hodges and Thorncroft, 1997; Balogun *et al*., 2023).

The development of convective systems in West Africa depends on the availability of moisture transported onto the continent by the monsoon winds. As discussed in Parker *et al*. (2005a,b), the dynamics of the low-level monsoon winds can be explained using a diurnal time frame. Their study (as well as others) emphasizes the importance of the formation of a Nocturnal Low-Level Jet (NLLJ) for the intrusion of moist air into West Africa (Lothon*et al*., 2008). The NLLJ is driven by the land sea pressure gradient that develops during the WAM season. During the daytime turbulent mixing increases the frictional force at the surface thereby causing a reduction in the low-level winds. After sunset (during the evening hours) turbulent mixing drops thus greatly reducing the frictional force at the surface. This allows the low-level winds to accelerate during the night where they reach a peak in the early morning (Blackadar, 1957; Persson, 2002a,b). During the night the NLLJ advects cool humid air into the Sahel, thereafter, during the day turbulent mixing redistributes these quantities in the vertical (Parker *et al*., 2005a,b). Using a 2D model, Peyrille and Lafore (2007) showed that the nocturnal advection of moisture via the NLLJ and the subsequent daytime turbulent mixing are critical for maintaining deep convective systems in the Sahel during the rainy season.Tanimoune et al. (2024) observed that the Model for Prediction Across Scales-Atmosphere (MPAS-A) simulate well the rainfall pattern and the different phases (northward progression, the peak period, and the southward retreat) of the monsoon dynamics system over west Africa, but underestimates the orographic rainfall over the Guinea Coast, Jos Plateau, and Mount Cameroon. The MPAS-A reasonably reproduces the pattern of the zonal

components of wind, but underestimates the zonal wind magnitudes over the region. The majority of rain produced in the Sahel, savannah and rainforest zones comes from Mesoscale Convective Systems (MCSs) (Lebel *et al.,* 2003), as a result, it is vital to investigate these systems, including the stratiform precipitation component.

Le Barbe *et al.* (2002) showed that the first rainy season starts on the coast around February and this onset shifts northward reaching around 13^0N, close to the Sudano zone around May. Mohr and Thorncroft (2006) in their study observed that the highest frequency of weak convective systems is often situated in the rainforest and savannah zones of West Africa (south of 10^0N) and were often shifted into the central African zone, whereas the highest occurrences of intense convective systems followed the seasonal migration of the African Easterly Jet (AEJ)northwards and become distinctly separated from the weak convective systems. Talib et al. (2022) noted a southward and northward shift of the monsoon based on dry and wet intraseasonal soil moisture events respectively. They also observed that the AEJ also responded to surface changes, such as a southward shift based on an increased temperature gradient during a dry event. Mohr (2004) noted that the seasonal cycle and highly variable ambient conditions modulate the initiation and growth of convective systems in rainforest and savannah zones (sub-Saharan Africa), the diurnal variability of precipitation could also be dynamic, and possessing both temporal (intraseasonal and interannual) and spatial (regional) variability depending on the scales.

Previous studies have indicated links between the African Easterly Jet (AEJ) and Sahelian precipitation (e.g. Diedhiou *et al.,* 1999; Cook 1999; Grist and Nicholson 2001),but have given less attention to the varying characteristics of the convective systems producing the precipitation in the Sahel. Janiga and Thorncroft (2014) analysed convective properties in the time scales of diurnal and July – September (JAS), which is not broad enough to cover early monsoon season particularly in the south and central zones of West Africa, and as a result, the variability during March – June was not captured in their work. The monsoon onset days have been shown to fall within this period in the rainforest and savannah zones of West Africa (Fontaine and Louvet, 2006; Nguyen *et al.,* 2011), which constitutes at least two of their zones. In order to investigate the diurnal variation at the early phase of the West African monsoon, there is need to include data starting from March as against those of previous authors who focused only on the Sahel zone and thus neglecting the early phase of the monsoon in Sub – Saharan Africa. Furthermore, the West African monsoon has been studied, mostly over the Sahel region. The regions in these studies were found to represent at least one large horizontal domain or box, and as a result, smoothing out variability in the domain. Some of these studies represented short time periods and far smaller domains when compared to satellite studies. To perform an in-depth analysis of the West African summer monsoon, and using data from Era-Interim reanalysis, this research work had divided West Africa into seven (7) zones/domains rather than one large horizontal domain, and longer time periods (sixteen years data, rather than selected days in previous studies). In this work, all the

zones are adjacent to each other within/inside the West African domain and large enough for sampling climatological data similar to (Janiga and Thorncroft, 2014; Balogun and Adeyewa, 2017) but with slight modifications. Increased awareness of zonal and meridional inhomogeneity of atmospheric features resulting from the AMMA project underscores the need for more detailed analysis within a smaller zonal domain. The specific objectives are to examine the diurnal variation of atmospheric features, moisture transport and convergence/divergence in smaller domains over west and central Africa.

2.0 DATA AND METHODOLOGY

2.1 Parameters from Era-interim Analysis

16-year (1998 to 2013) 6-h interval European Centre for Medium-range Weather Forecasts (ECMWF) Reanalysis Interim (ERA-Interim: Simmons *et* al., 2007; Dee *et al*., 2011) dataset (0.75^0 x 0.75^0) was used for this work. Because of the better reputation and higher horizontal resolution of ERA-Interim analysis; this research work decided to use ERA-Interim analysis to investigate the wind and moisture fluxes. The reanalysis merges observations and model data across the globe using the data assimilation principle. Thirty-seven pressure levels were used for the profiles. The pressure levels are: 1.0, 2.0, 3.0, 5.0, 7.0, 10.0, 20.0, 30.0, 50.0, 70.0, 100.0, 125.0, 150.0, 175.0, 200.0, 225.0, 250.0, 300.0, 350.0, 400.0, 450.0, 500.0, 550.0, 600.0, 650.0, 700.0, 750.0, 775.0, 800.0, 825.0, 850.0, 875.0, 900.0, 925.0, 950.0, 975.0, and 1000.

The parameters used are shown in Table 1.Mathon *et al*., 2002)

Table 1: ERA – Interim parameters used for analysis.

q	Specific humidity
U	Zonal wind profile
V	Meridional wind profile

2.2 DERIVED PRODUCTS

Besides the wind and specific humidity profiles; moisture fluxes, moisture transport, and vertically integrated moisture flux convergence (VIMFC) were also analysed using the following relations:

$$F_V = \int_0^T -\frac{1}{g}\left(\int_{p_b}^{P_t} q\mathbf{u}dp\right)dt$$

$$Q = \int_0^T \frac{1}{g}\left(\int_{p_b}^{P_t} \nabla.\, q\mathbf{u}dp\right)dt$$

Where F_v is the moisture flux transport, Q is the vertically integrated moisture flux convergence, *g* is gravitational acceleration, *q* is specific humidity, **u** is the two-dimensional wind, p_t and p_b represent the pressure at the top and bottom of the layer concerned and is the averaging period.

Following (Cadet and Nnoli, 1987; Thorncroft*et al.,* 2011), this work considered only the seasonal (MAM) mean of the zonal vertically integrated moisture transport between 1000 and 850mb (the approximate depth of the monsoon layer), and between 850 and 500mb to highlight the moisture transport at midlevels. The two (2) components of the zonal moisture transport are (i) the westerly component, indicated by the positive (+) contour values, and (ii) the easterly component, indicated by negative (-) contour values.

2.3 Study Area

In this study, the West African region is divided into seven zones (Balogun *et al*., 2019) as follows;

west-coast rainforest, dry rainforest, Nigeria-Cameroon rainforest ((three rainforests)), Central Africa and South Sudan (CASS) savannah, Nigeria savannah (two savannah), and Sudano-Sahel and Sahel (two Sahel). These seven (7) zones which constituted the study area are presented in Figure 1. The rainfall and vegetation characteristics of the seven (7) zones are presented in Table 2.See Balogun et al., 2019 (https://link.springer.com/article/10.1007/s00704-018-2692-1) for detailed description of each of the zones.

3.0 RESULTS AND DISCUSSION

3.1 Profiles of Wind And Moisture Flux

3.1.1 West Coast Rainforest Zone

The profiles of wind and moisture fluxes, at the diurnal scale during March-May (MAM), for the west-coast rainforest zone are shown in Figure 2 (a – d). The zonal and two (2) dimensional (hereafter referred to as 2D) components of the wind and moisture fluxes, Figures 2a and c, indicate that this southwesterly influx of moisture only slightly varies at six hours intervals, and always at its peak depth during the morning hours (6Z), where Z (zulu) is the Universal Time Coordinate (UTC). This agrees with Parker *et* al., (2005a) that the West African monsoon winds often intensify at night when the Boundary Layer turbulence is much weaker. There is no significant diurnal variability at mid-levels (850 – 400mb). The diurnal profiles in this zone, which is situated in the western axis of West Africa with coastal landmass, for the zonal and 2D easterly winds and fluxes showed the presence of African Easterly Jet (AEJ) at all six hourly intervals. The zonal and 2D southwesterly moisture fluxes, and hence the monsoon depth, agree with the wind components

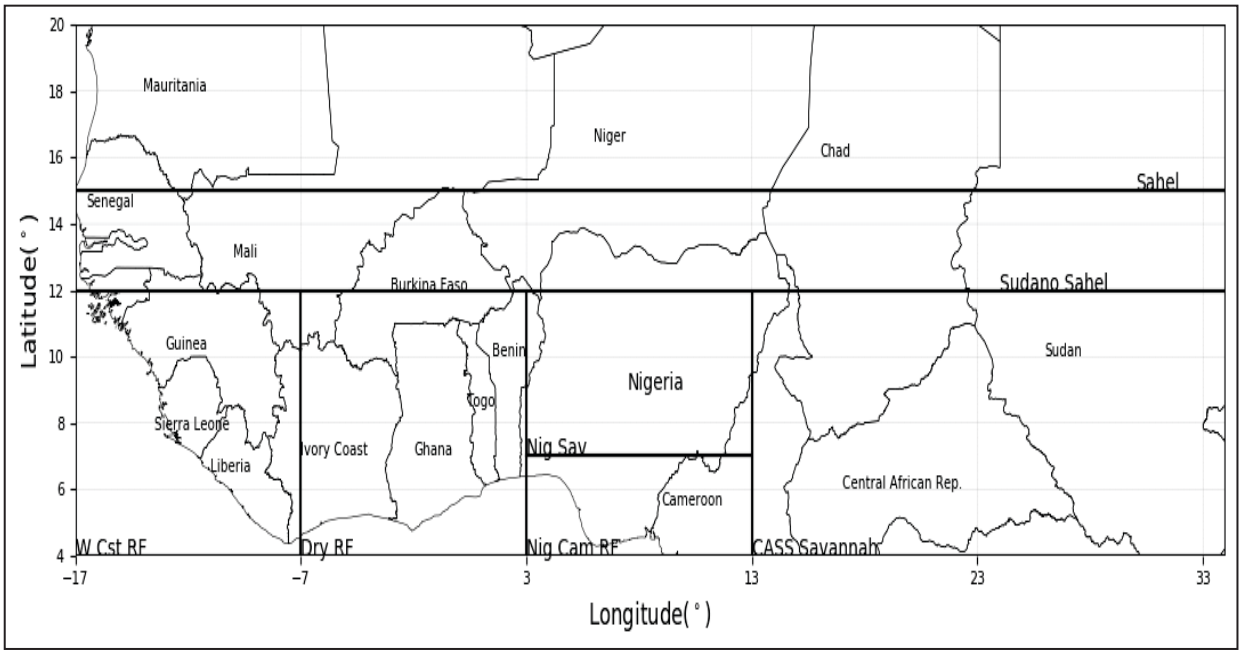


Figure 1: Study area showing the seven (7) selected climate zones(W_Cst_RF: West Coast Rainforest; Dry_RF: Dry Rainforest, Nig_Cam_RF: Nigeria_Cameroon Rainforest, CASS Savannah: Central Africa and South Sudan Savannah; Nig_Sav: Nigeria Savannah, Sudano_Sahel, and Sahel).
Source: Modified after Adeyewa*et al*., 2005 and Balogun and Adeyewa (2017).

Table 2: Summary of rainfall and vegetation characteristics of the study zones.

SUB-REGIONS	MIN. LAT	MAX. LAT	MIN. LON	MAX. LON	ANNUAL RAINFALL	VEGETATION
W_CST_RF	4	12	-17	-7	Up to 3,300mm	Forest is dense with trees reaching over 60m.
DRY_RF	4	12	-7	3	1500 – 2000mm	Forest canopy is dense and closed, forming over a heterogeneous woody understory. Tree height is high averaging 18-20m.
NIG_CAM_RF	4	7	3	13	2000 – 3500mm	Montane vegetation.
CASS SAVANNAH	4	12	13	34	600 – 1000mm	Sudd Swamps. Woody Savannah composed mainly of Combretum and Terminalia shrub, tree species and tall elephant grass.
NIG_SAVANNAH	7	12	3	13	1000 – 1500mm	Vegetation differs from season to season. Tall grasses are common during wet season.
SUDANO_SAHEL	12	15	-17	34	400 – 900mm	The domain of savannah – ranging from open tree savannah to open woodlands. Tall perennial grasses.
SAHEL	15	20	-17	34	100 – 200mm	Stunted and scattered trees, shrubs, bushes, and grasses.

by their night (0Z) and morning hours (6Z) peak monsoon depths than the other periods of the day. Another observation is the presence of a Low-Level Jet (LLJ) in the west coast rainforest during the MAM season similar to the findings by Kalthoff *et al*. (2018) but for field campaign sites of Kumasi (Ghana), Ile-Ife (Nigeria) and Save (Benin). At upper levels, in Figure 2 (a – c), a weak subtropical westerly jet is imminent in the west coast rainforest zone during the MAM season. The meridional wind and moisture flux profiles, Figure 2b, were more highly variable at 6-hour intervals than its zonal and 2D components. All features (LLJ, AEJ, and subtropical jet) observed in the zonal and 2D components were also indicated by the meridional component of the wind. The meridional component of the wind and moisture fluxes was stronger, although weaker when compared with the zonal wind component, at night than in the morning hours and other periods of the day. The specific humidity, in Figure 2 (d), is relatively the same at all times of the day, and at all levels.

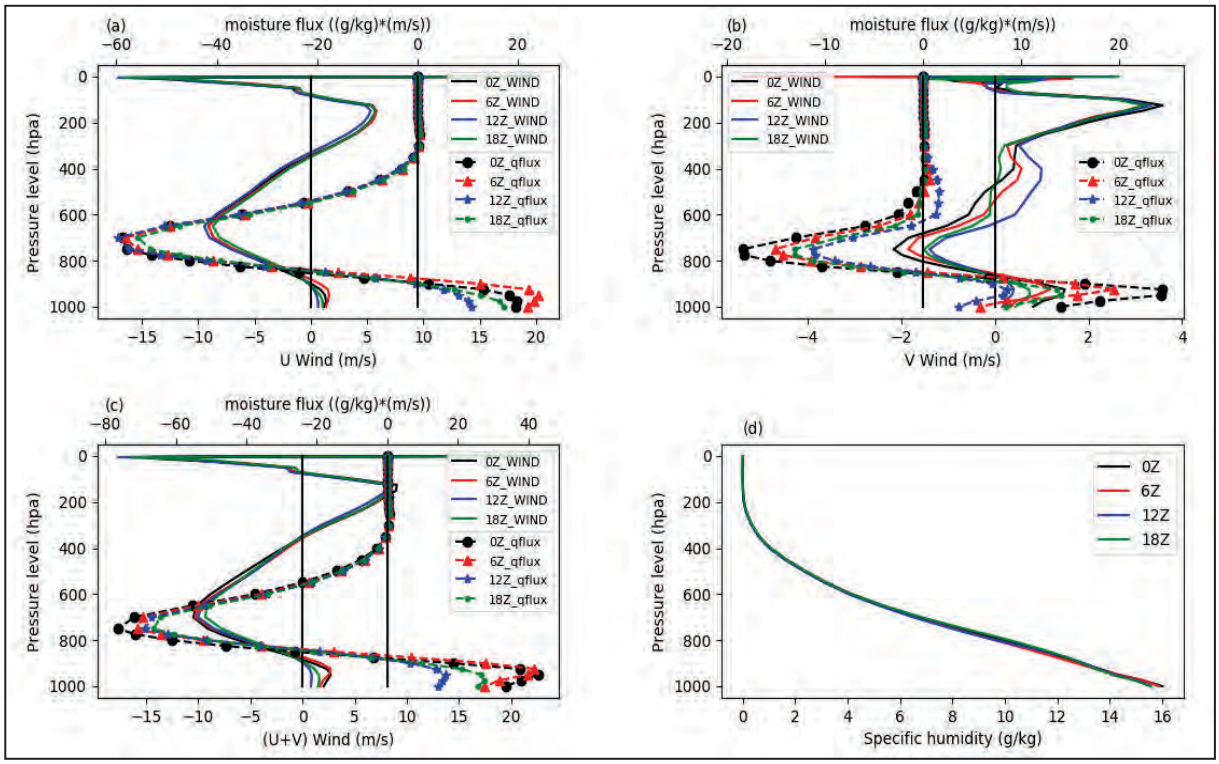


Figure 2 (a – d): Profiles of wind and moisture fluxes for (a) zonal component (b) meridional component (c) 2-dimensional component, and (d) specific humidity profile, in west coast rainforest zone during MAM.

3.1.2 Dry rainforest zone

The wind and moisture flux patterns in the Dry rainforest are very similar to the observed pattern in west-coast rainforest earlier discussed. These two (2) zones share boundaries but have slightly different climate/vegetation characteristics. In (a and c), similar to the west-coast rainforest, during the MAM season, the monsoon depth is close to 850mb, there is the presence of the African Easterly Jet (AEJ) around 650mb, and the presence of the subtropical jetstream at around 200mb, as indicated by the zonal and 2D wind profiles. The zonal and 2D moisture fluxes in the Dry rainforest zone are extremely stronger than for the west-coast rainforest, reaching a maximum of about 100 (g/kg*m/s) during the night (0Z) and morning (6Z) hours. The 6-hour variability is more pronounced as indicated by the 2D component of the southwesterly wind profiles. In this zone, as was observed in the west-coast rainforest zone, the night and morning time winds are stronger than the other times of the day. In Figure 3(b), meridional wind variability is more pronounced at mid-levels, with peak easterlies indicated by the night (0Z) and morning (6Z) time. Figure 3(d) shows a slightly different specific humidity profile when compared to what was observed in the west-coast rainforest zone. There is slight variability up to about 700mb, thereafter the four diurnals seem to be consistent to the top of the atmosphere. The presence of the Nocturnal Low-Level Jet (NLLJ) is also imminent. This NLLJ has been shown to form close to the Low-Level Cloud (LLC) layer as defined by Kalthoff *et al*. (2018). This zone contains two of the supersites used by Kalthoff *et al*. (2018) for their

field campaigns.

3.1.3 Nigeria-Cameroon Rainforest Zone

Unlike the previous two (2) zones discussed, in Figure 4 (a and c) the first important observation or finding in this zone is the absence of the upper-level westerly subtropical jet during the MAM season. The zone has a deeper monsoon depth than the west-coast and Dry rainforest zones, with a peak close to 800mb. The variability of the 6-hour periods was minimal at all levels, both for the zonal and 2D components of the wind. The surface southwesterly moisture fluxes indicated stronger variability at the different diurnals with peak values of 40 (g/kg*m/s) and 80 (g/kg*m/s) for the zonal and 2D components respectively during the night time (0Z) in both cases. The strength of the African Easterly Jet (AEJ) is consistent with the west-coast and Dry rainforest zones. It is surprising that the meridional component, Figure 4(b), established the presence of the upper-level subtropical jet, unlike the zonal and 2D components. The meridional component of the wind and moisture fluxes seems to be a little stronger in this zone during MAM than in the previous two (2) zones in the same season. The specific humidity profiles, Figure 4(d), only indicated minimal variability close to the surface.

3.1.4 Nigeria Savannah Zone

This zone, in Figure 5 (a–c), shows the presence of African Easterly Jet (AEJ) and subtropical westerly jet in the intensity of the west-coast and Dry rainforest zones. The monsoon moisture depth in the MAM season is at about 850mb as observed in the west-coast and Dry rainforest

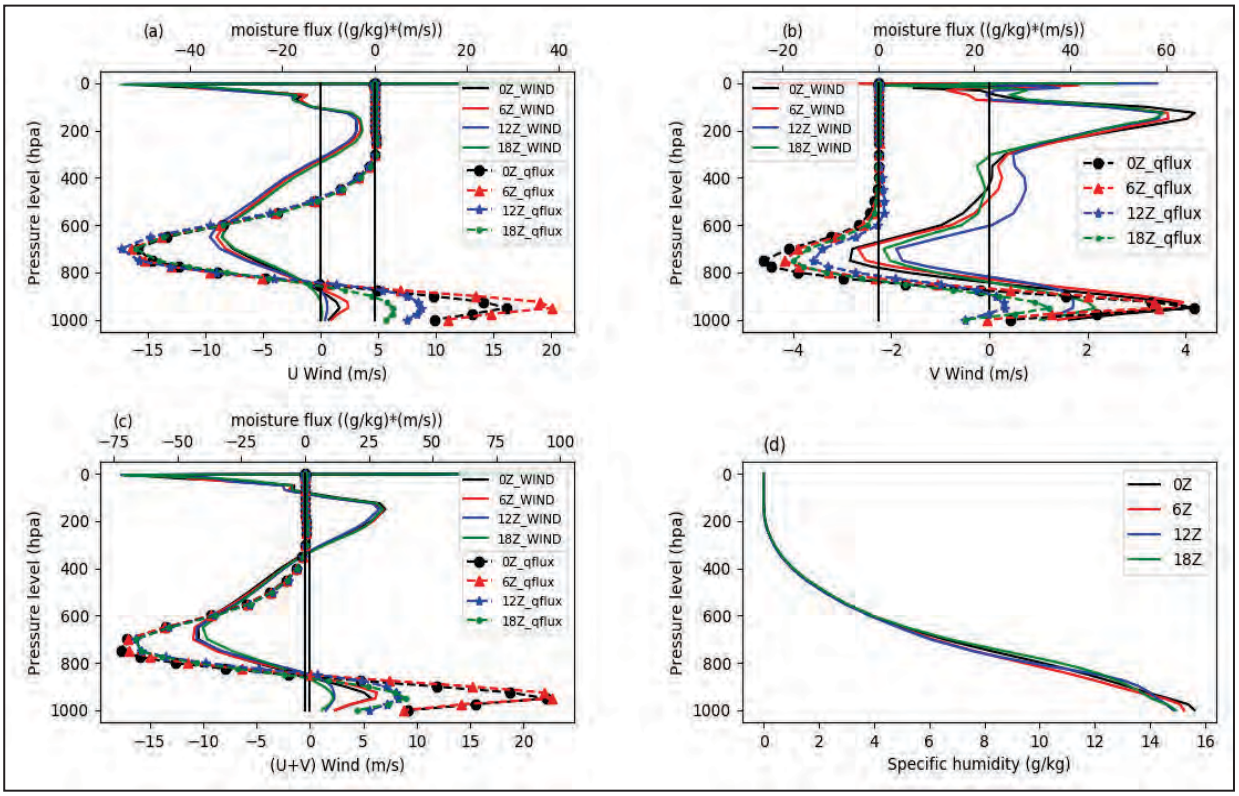


Figure 3(a – d): Profiles of wind and moisture fluxes for (a) zonal component (b) meridional component (c) 2-dimensional component, and (d) specific humidity profile, in dry rainforest zone during MAM.

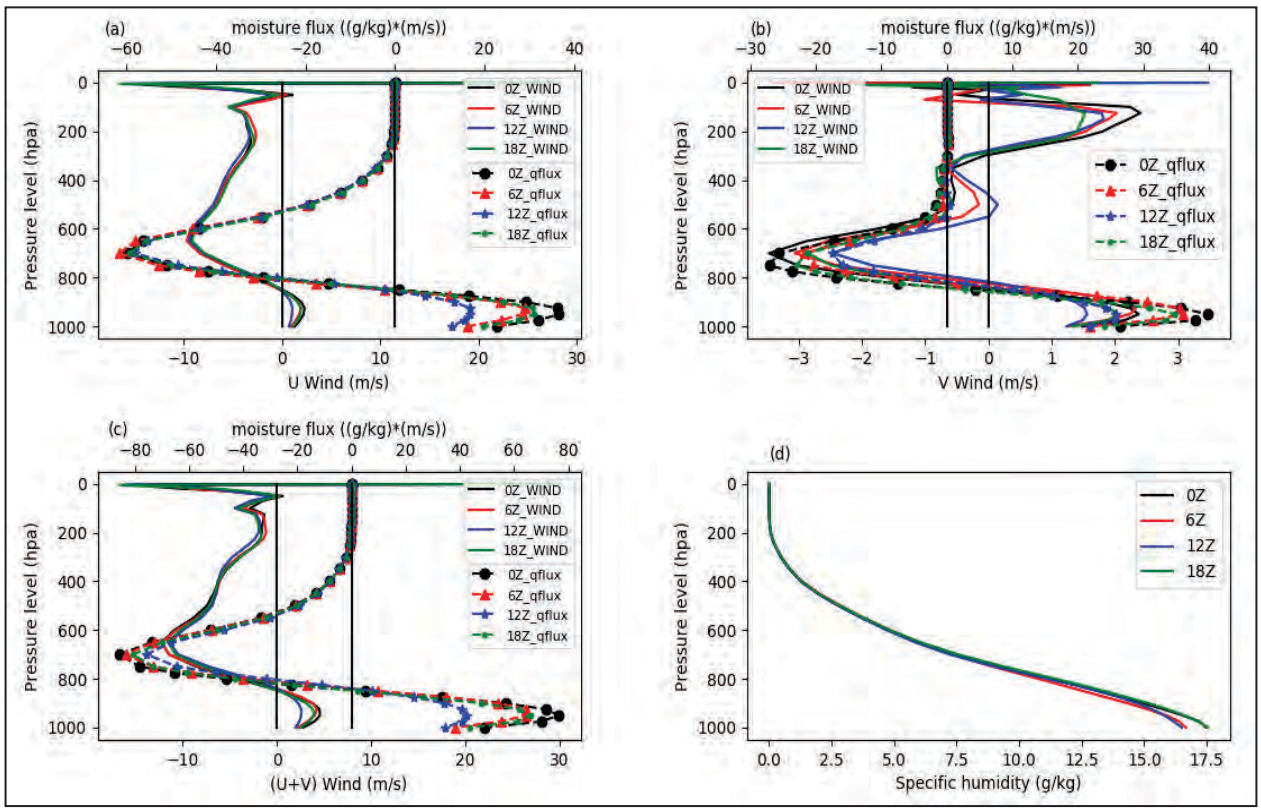


Figure 4 (a – d): Profiles of wind and moisture fluxes for (a) zonal component (b) meridional component (c) 2-dimensional component, and (d) specific humidity profile, in Nigeria-Cameroon rainforest zone during MAM.

zones. There is also no significant diurnal variability in the 6-hour wind profiles, but the 6-hour diurnal moisture flux profiles indicated some variability for the surface southwesterly flow with peak values of 30 (g/kg*m/s), 40 (g/kg*m/s), and 80 (g/kg*m/s) indicated by the zonal (Figure 5a), meridional (Figure 5b), and 2D (Figure 5c) components of the moisture fluxes respectively at the night (0Z) and morning hour (6Z) periods in all the three moisture flux components. The specific humidity profiles for the Nigeria Savannah zone, in Figure 5(d), are also consistent particularly from about 750mb to the top of the atmosphere.

3.1.5 Central Africa and South Sudan (CASS) Savannah Zone

The zonal component (Figure 6a) of the southwesterly monsoon flow, rarely enters the Central Africa and South Sudan (CASS) Savannah zone during the MAM season, but the 2D component (Figure 6c) of the southwesterly monsoon flow shows that the monsoon flow could only be established during the night (0Z) and morning (6Z) hours. The presence of the African Easterly Jet (AEJ) and a weaker subtropical westerly jet is also established in this zone during the MAM season. Given the low values of the peak moisture fluxes, which are less than 5 (g/kg*m/s) for the zonal component (Figure 6a) of the moisture fluxes and only about 40 (g/kg*m/s) for the 2D component (Figure 6c) of the moisture fluxes, it is quite obvious that this zone is rarely influenced by the monsoon rainfall during the MAM season. The meridional southwesterly wind and moisture flux components (Figure 6b)

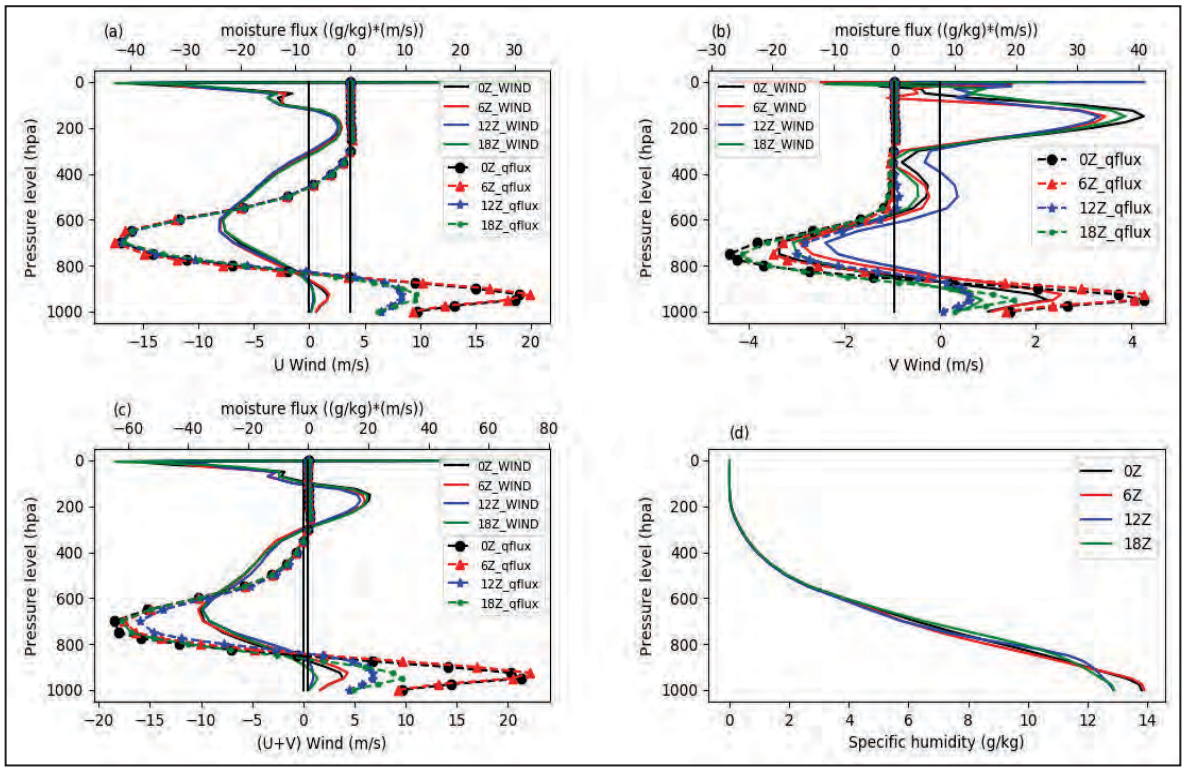


Figure 5(a – d): Profiles of wind and moisture fluxes for (a) zonal component (b) meridional component (c) 2-dimensional component, and (d) specific humidity profile, in Nigeria savannah zone during March–May (MAM).

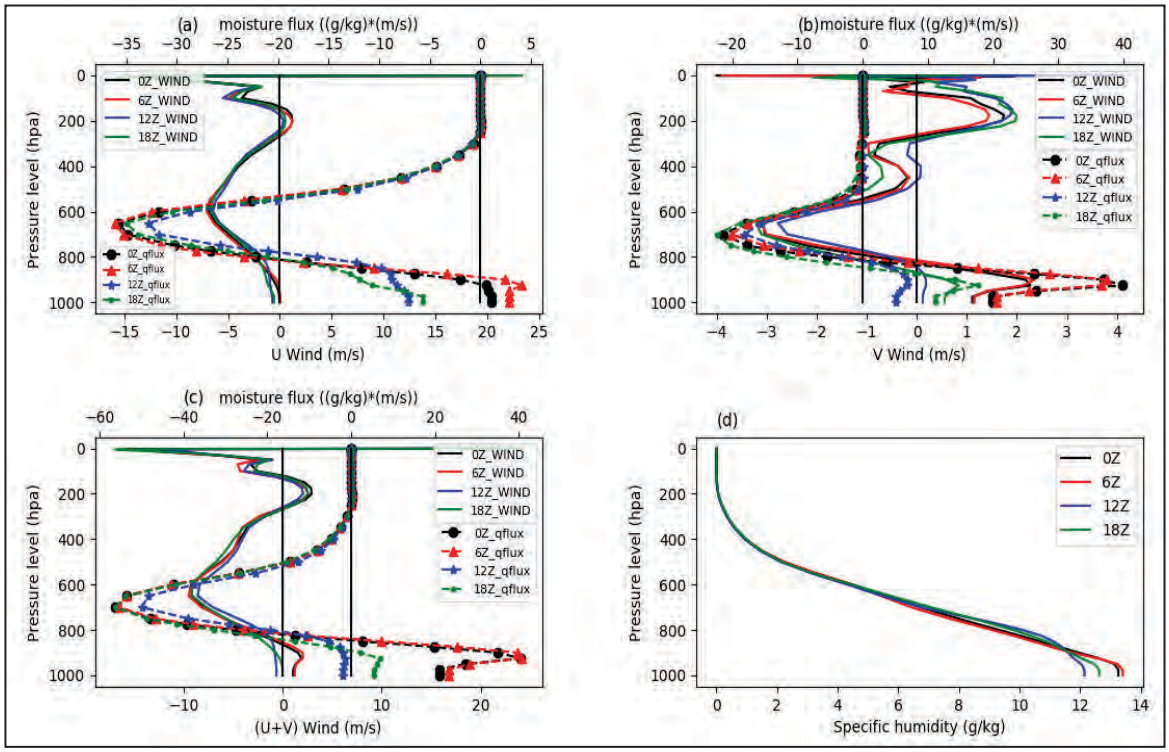


Figure 6(a – d): Profiles of wind and moisture fluxes for (a) zonal component (b) meridional component (c) 2-dimensional component, and (d) specific humidity profile, in CASS savannah zone during March–May (MAM).

arewell established in the CASS Savannah zone but this wind alone does not usually account for moisture buildup. In this zone as observed in the previous zones discussed earlier, the night (0Z) and morning (6Z) hours have peak values of both wind and moisture fluxes. The specific humidity, in Figure 6(d), was slightly lower in this zone, with peak surface values at the night (0Z) and morning (6Z) periods not exceeding 14 g/kg as against the previous zones in which the surface diurnals reached peak values of about 16 g/kg.

3.1.6 Sudano – Sahel Zone

As shown in Figure 7 (a–c), there is obviously no presence of the African Easterly Jet (AEJ), no monsoon flow into the Sudano – Sahel zone, and the winds and moisture fluxes are generally weak during the MAM season in this zone. The presence and hence intensity of the subtropical westerly jet is stronger in the Sudano zone than in the southern zones of the Guinean subregion. There are pronounced 6-hour variabilities in the zonal (Figure 7a), meridional (Figure 7b) and 2D (7c) components of both the winds and moisture fluxes reaching up to the 600mb level as this is evident in the 6-hour diurnal variability of the specific humidity profiles (Figure 7d). The meridional wind and moisture fluxes (Figure 7b) indicated a weak easterly jet at the 850mb level. The peak values of the surface moisture fluxes are about 5 (g/kg*m/s), 5 (g/kg*m/s), and 10 (g/kg*m/s) for the zonal, meridional, and 2D components respectively and were attained during the morning hours.

3.1.7 Sahel Zone

Figure 8 (a–c) shows the presence of the subtropical westerly jet at upper levels and a weak

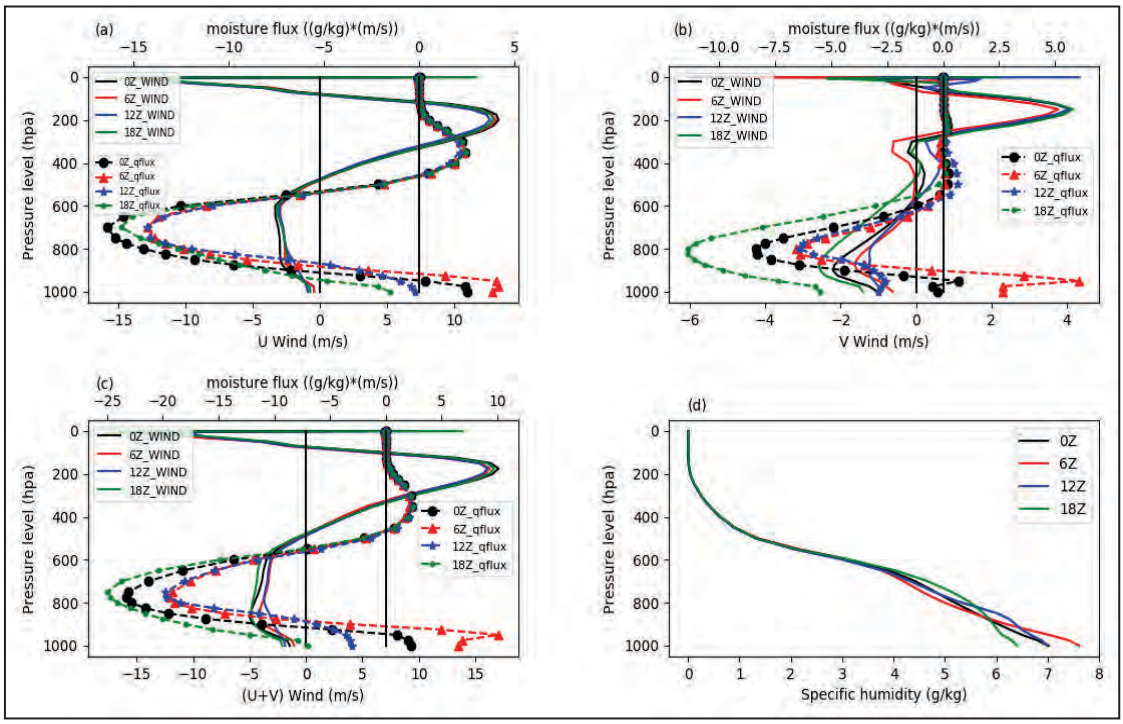


Figure 7(a – d): Profiles of wind and moisture fluxes for (a) zonal component (b) meridional component (c) 2-dimensional component, and (d) specific humidity profile, in the Sudano – Sahel zone during March–May (MAM).

Low-Level Easterly Jet (LLEJ) between the 1000mb and 800mb levels. The winds and moisture fluxes are weak compared to values in the southern Guinean zones but are within the same ranges as in the Sudano zone during the MAM season. The subtropical westerly jet has a peak value close to 25 m/s observed in the zonal wind component (Figure 8a). The moisture fluxes have peak easterly components during the night (0Z) and morning (6Z) periods shown by the zonal (Figure 8a), meridional (Figure 8b), and 2D (Figure 8c) components. The 6-hour variability was only significant in the meridional component of the winds and moisture fluxes as were observed in all the previous zones, but it is found to slightly vary up to the 600mb in the zonal (Figure 8a) and 2D (Figure 8c) components. The variability in the 6-hour diurnals up to the 600mb pressure level is evident in the specific humidity profiles in Figure 8(d). There is significantly low specific humidity during the MAM season as shown in Figure 8(d), with peak values of about 4.5 g/kg during the morning (6Z) hour.

3.1.8 Intercomparison of Moisture Fluxes among the Zones

To summarise the discussions in sections 3.1.1 to 3.1.7, this section presents an intercomparison of the moisture fluxes among the zones. The mean 24-hr (daily) diurnal moisture fluxes for the MAM season, as shown in Figure 9 (a – d), shows that the three rainforest zones and two savannah zones are already dominated by the south–westerly surface monsoon flow as indicated by the presence of

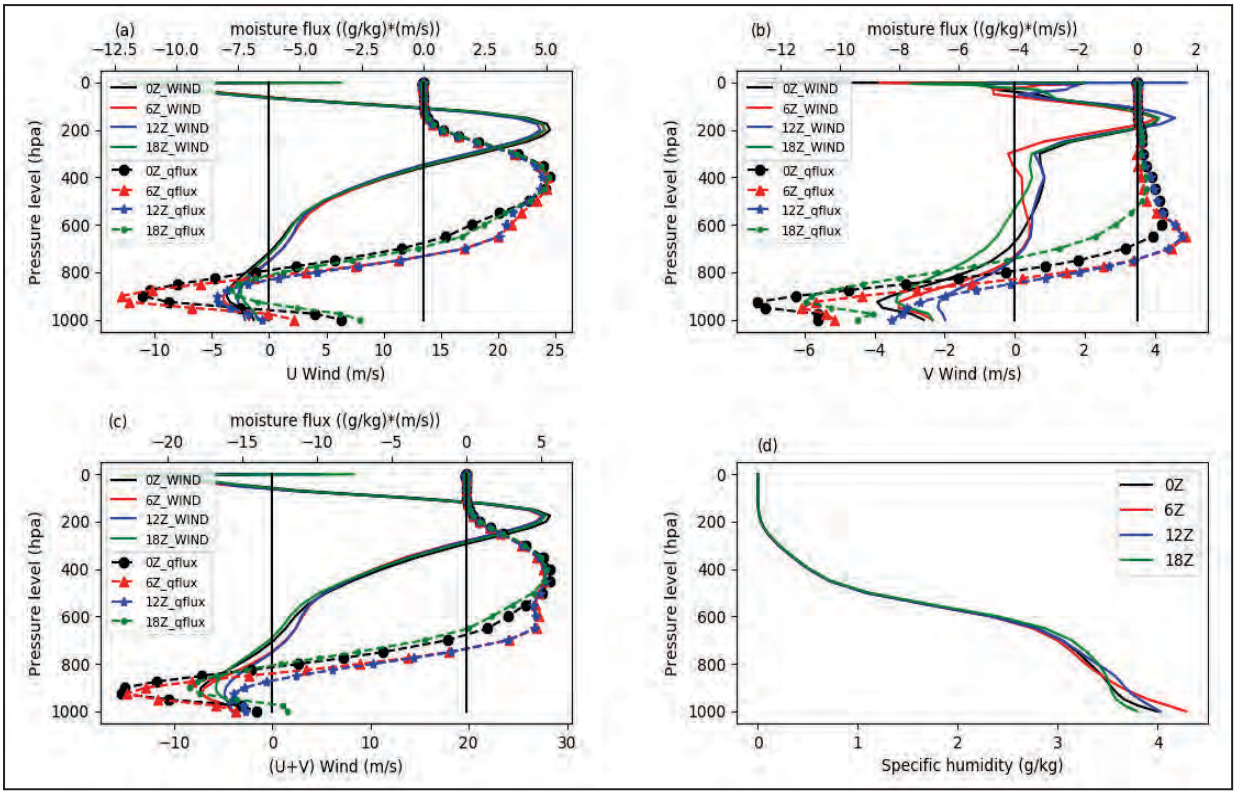


Figure 8(a – d): Profiles of wind and moisture fluxes for (a) zonal component (b) meridional component (c) 2-dimensional component, and (d) specific humidity profile, in Sahel zone during March–May (MAM).

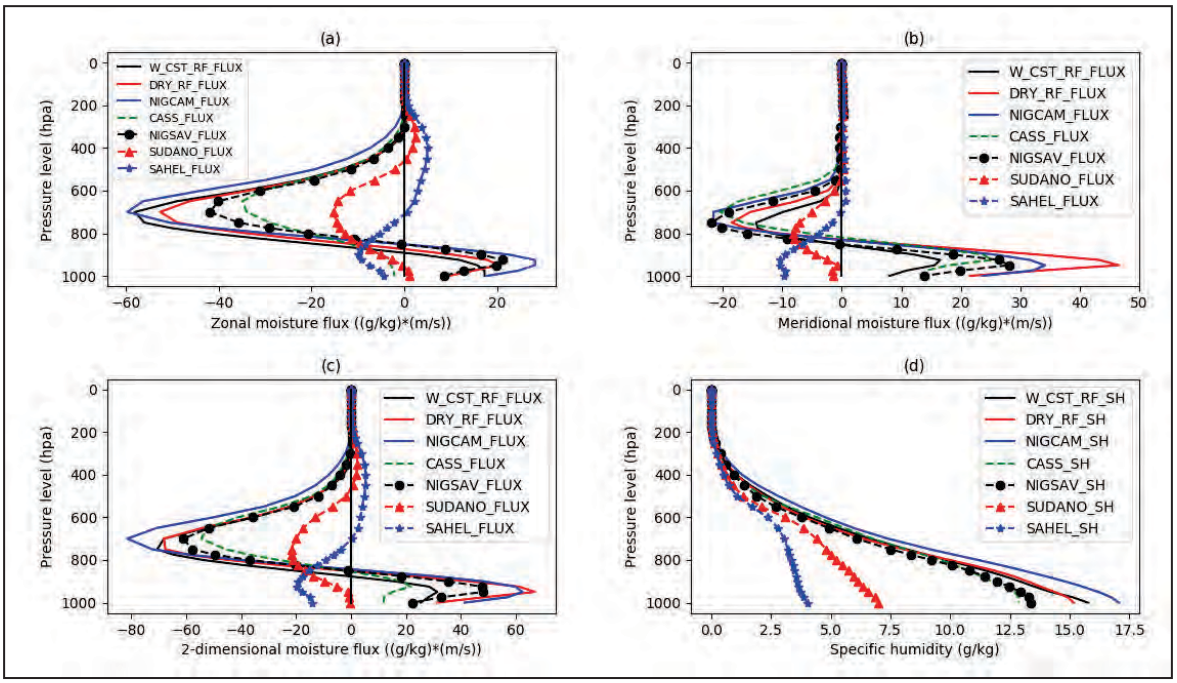


Figure 9(a – d): Comparison of mean daily profiles of moisture fluxes for (a) zonal component (b) meridional component (c) 2-dimensional component, and (d) specific humidity profile, during March–May (MAM).

strong moisture fluxes (Figures 9 (a – c)) and specific humidity (Figure 9d). The meridional component (Figure 9b) seems to have a stronger influence than the zonal component (Figure 9a), with fluxes reaching about 45 (g/kg*m/s) in the Dry rainforest zone and specific humidity greater than 10 g/kg at the 800 mb pressure level. As expected, the Sahel and Sudano zones are not influenced by the south–westerly monsoon flow during the MAM season. The Nigeria – Cameroon rainforest zone shows the highest specific humidity profile than the other zones. Strong surface specific humidity variability is also observed among the zones during the MAM season.

3.1.9 Latitudinal Cross-section: MAM

The zonally averaged latitudinal cross-section is shown in Figure 10 (a – d) for the MAM season. Three important features represented in the Figures are (i) the presence of the upper-level subtropical westerly jet at all the 6-hour periods, (ii) the presence of the African Easterly Jet (AEJ) at all the 6-hour periods, and (iii) the presence of the monsoon layer also at all the 6-hour diurnals. The depth of the monsoon layer is observed to be deepest during the night (0Z, Figure 10a) and morning (6Z, Figure 10b) hours, in latitudes between 4°N and 12°N during the MAM season. The African Easterly Jet (AEJ) is also observed close to the 600mb in the Guinean latitudes. The upper-level subtropical westerly jet which extends into the Guinean zones is strongest at higher latitudes such as in the Sahel zone. The peak values of the subtropical jet, African Easterly Jet (AEJ), and monsoon depth (moisture fluxes indicated by contour line) were ~40 m/s, ~-25 m/s, and ~20 (g/kg*m/s) at all the 6-hour diurnals. The

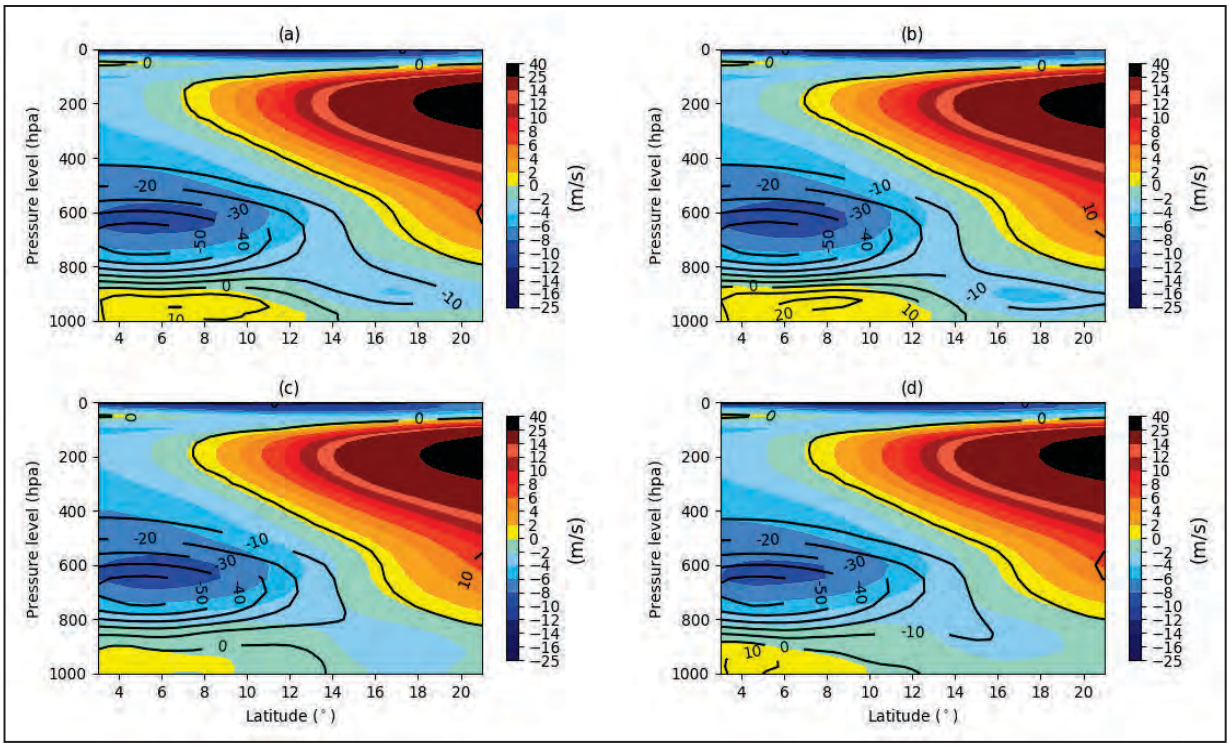


Figure 10 (a – d): Zonally averaged vertical cross section of wind (filled contour) and moisture flux (contour line) for (a) 0Z (b) 6Z (c) 12Z, and (d) 18Z during MAM.

monsoon layer is rarely deep during the day (12Z, Figure 10c) and evening (18Z, Figure 10d) hours. In summary, the African Easterly Jets (AEJ) and the monsoon layer are imminent at lower latitudes during the MAM season whereas the subtropical westerly jets are imminent at higher latitudes during the MAM season in West and Central Africa.

3.2 Moisture flux transport

Figure 11 (a – d), depicts the surface (low levels, 1000 – 850mb) westerly moisture transport onshore during the night (0Z, Figure 11a), morning (6Z, Figure 11b), day (12Z, Figure 11c), and evening (18Z, Figure 11d), it is observed that the surface (low levels, 1000 – 850mb) monsoon westerly moisture are consistently transported into four (4) zones (west-coast rainforest, dry rainforest, Nigeria-Cameroon rainforest, and Nigeria Savannah) south of 12°N during the MAM season, particularly during the night (0Z) and morning (6Z) hours. Only some parts of the Nigeria-Cameroon rainforest (onshore), comprising southern Nigeria are the transport of surface (low levels, 1000 – 850mb) westerly moisture dominant during the day (12Z) and evening (18Z) hours. Figure 11 (a – d) shows that the Central Africa and South Sudan (CASS), Sudano, and Sahel zones are characterized by the surface (low levels, 1000 – 850mb) easterly trade winds, particularly during the day (12Z, Figure 11c) and evening (18Z, Figure 11d) hours. Peak values of moisture fluxes in the four (4) zones earlier mentioned were in the range of 100 – 160 kg m^{-1} s^{-1}, similar to results from Thorncroft*et al.*, 2011, and located in the southeastern zone of Nigeria and close to the Nigeria/Cameroon boundary. These peak values, during the MAM

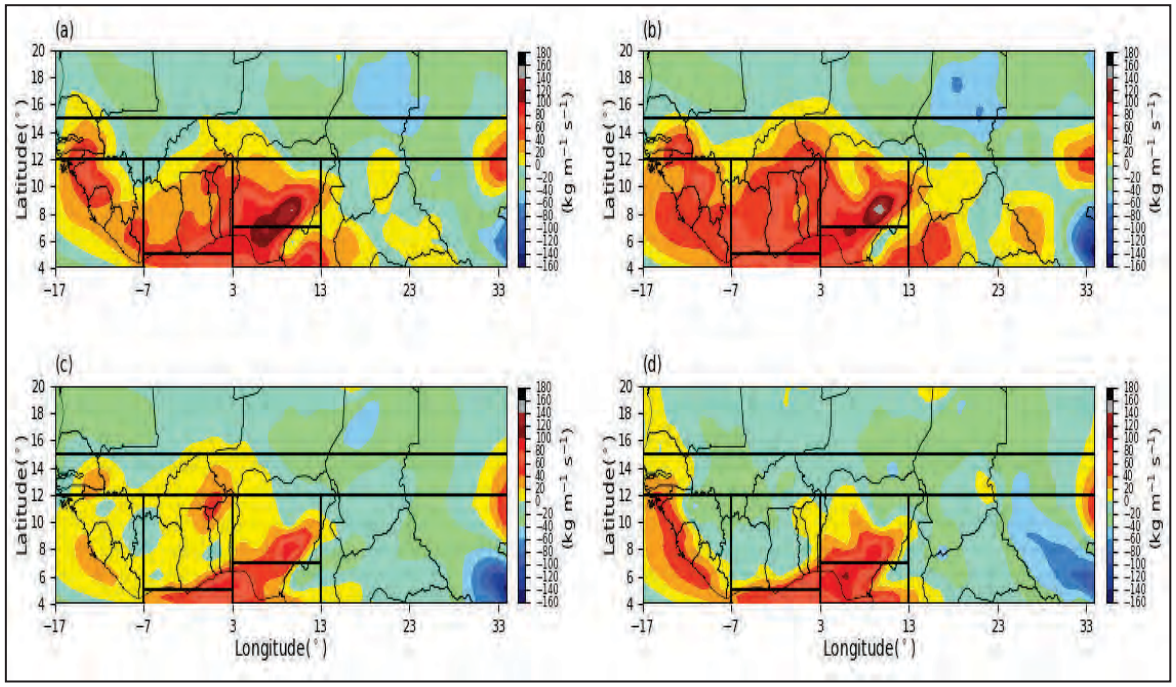


Figure 11(a – d): Zonal moisture transport at low levels (1000 – 850mb) for (a) 0Z (b) 6Z (c) 12Z, and (d) 18Z during March–May (MAM).

season, are observed to be strongest during the night (0Z) and morning (6Z) hours.

At mid-levels (Figures 12a – d), during the MAM season, all the zones particularly, the west-coast rainforest, dry rainforest, Nigeria-Cameroon rainforest, and Nigeria Savannah, south of 12°N are characterized by strong easterly moisture transports possibly due to the presence of the African Easterly Jet (AEJ) in these zones. The mid-levels of the Sudano and Sahel zones are characterized by weaker easterly moisture transport during the MAM season. Peak values are in the range of 160 – 220 kg m^{-1} s^{-1}.

3.3 Moisture flux convergence

In an environment that was already saturated with moisture, as in the cases of zones in this study, where monsoonal moisture had been transported, some of the boundary layer processes required for the development of moist convection (convection initiation) are instability and a trigger mechanism like vertical motion. The latter process is needed to release the available energy for convection. Moisture flux convergence (MFC) is a term in the conservation of water vapour equation and was first calculated in the 1950s and 1960s as a vertically integrated quantity to predict rainfall associated with synoptic-scale systems (Banacos and Schultz, 2005). The Vertically Integrated Moisture Flux Convergence (VIMFC) in the lowest 3 km of the atmosphere consists of two terms: a term proportional to the convergence of the horizontal wind vector and a second term that is proportional to moisture advection, sometimes referred to as "moisture pooling." The first term is often the largest. This term is associated with forced lifting. By combining the influence of forced lifting and moisture pooling in one parameter, VIMFC incorporates the ingredients necessary for convection initiation that are not taken into account in traditional thunderstorm

indicators (van Zomeren and van Delden, 2007).

In Figure 13, negative (-) values indicate convergence and positive (+) values indicate divergence. During the MAM season, the development of convection, as depicted by the combined (2D wind component) vertically integrated (1000 – 850mb) moisture flux convergence, is observed to be consistent along the Nigeria/Cameroon boundary axis during all the 6-hr periods, in Sierra Leone of west-coast rainforest during the night (0Z, Figure 13a) and morning (6Z, Figure 13b) periods, and in the eastern axis of the Central Africa and South Sudan (CASS) Savannah during the morning (6Z, Figure 13b) and day (12Z, Figure 13c) diurnals, for the MAM season. The Nigeria Savannah zone was observed to be a divergence zone for the MAM season. Extremely weaker convergence and divergence are observed in the Sudano and Sahel zones at all periods for the MAM season. A dipole of moisture flux convergence and divergence are observed between the Nigeria Savannah zone and Central Africa and South Sudan zone in the MAM season.

The vertically integrated moisture flux convergence at mid-levels (850 – 500mb) for the MAM season is shown in Figure 14 (a – d). In the MAM season, all the zones (onshore) indicated mild or weak vertically integrated moisture flux convergence at mid–levels during all the 6-hr periods. The occurrence of moisture convergence at mid–levels during MAM simply implied that convergence is deep (low levels through mid–levels) into the atmosphere and hence strong development of convection in the atmosphere during this season.

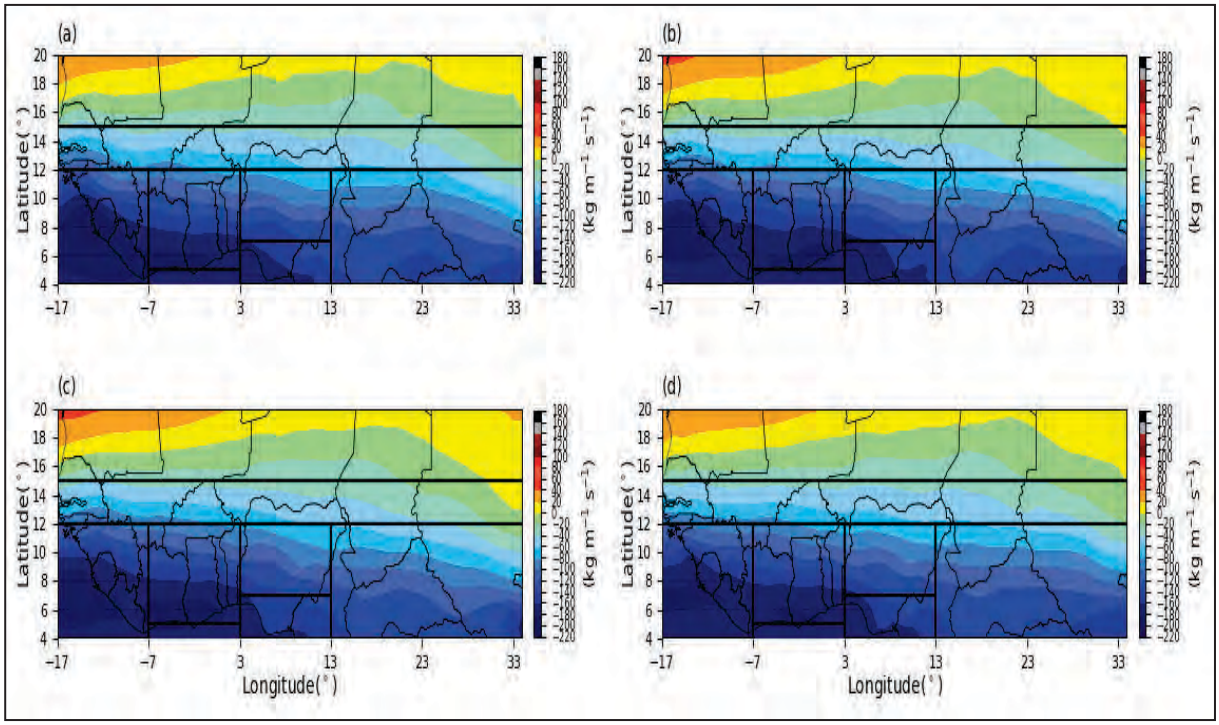


Figure 12(a – d): zonal moisture transport at mid-levels (850 – 500mb) for (a) 0Z (b) 6Z (c) 12Z, and (d) 18Z during March – May (MAM).

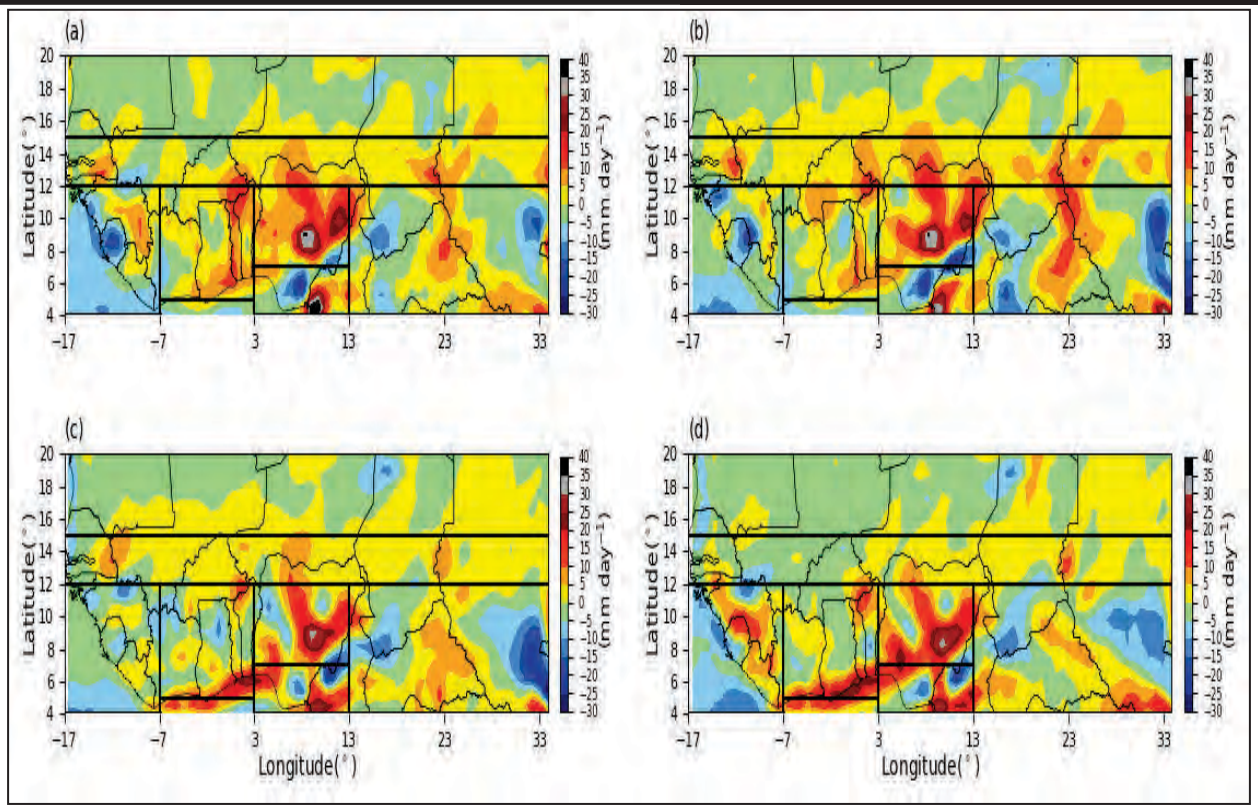


Figure 13(a – d): Moisture flux convergence at low levels (1000 – 850mb) for (a) 0Z (b) 6Z (c) 12Z, and (d) 18Z during March–May (MAM).

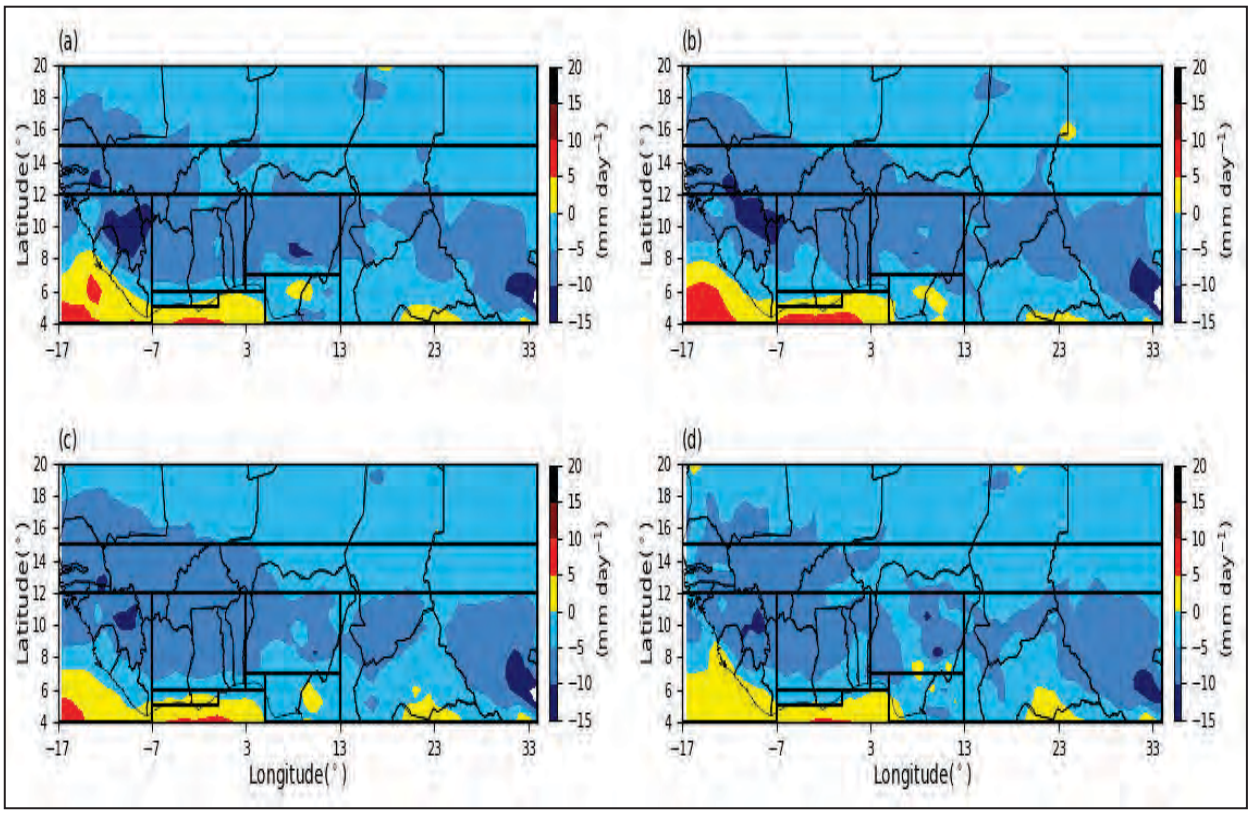


Figure 14(a – d): Moisture flux convergence at mid-levels (850 – 500mb) for (a) 0Z (b) 6Z (c) 12Z, and (d) 18Z during March–May (MAM).

4. CONCLUSION

The diurnal variation, at the early phase (March to May), of the West African monsoon has been investigated. The monsoon onset days consistently fall within this period in the rainforest zones of West Africa. The results include the absence of the Tropical Easterly Jet and the presence of a weak westerly subtropical jet in west-coast and dry rainforest zones, Nigeria Savannah and Central African and South Sudan Savannah (CASS) zones.The westerly subtropical jet surprisingly is not present in the Nigeria-Cameroon zone, which is a rainforest zone. The African Easterly Jet (AEJ) is not present in the Sudano and Sahelian zones but the subtropical westerly jets are strongest in these two zones than the southern Guinean zones. The monsoon wind is often at its peak during night and morning hours in most of the zones. The moisture fluxes are strongest in the dry rainforest zone, which is westward of the west coast rainforest zone, compared to the other zones. In summary, the AEJ and the monsoon winds are imminent at lower latitudes in MAM season, whereas, the subtropical westerly jets are imminent at higher latitudes in MAM season. The monsoon flow into the CASS savannah zone is very weak in MAM, which makes it obvious that the zone is rarely influenced by the monsoon rainfall in MAM season. The study observed diurnal variability in the surface specific humidity in the dry rainforest and the two Sahelian zones, while the Nigeria-Cameroon rainforest zone had the highest specific humidity profile than the other zones. The surface westerly monsoon is consistently transported into four (4) zones (west coast, dry and Nigeria-Cameroon rainforest zones, and Nigeria-Savannah zone), which are south of 12°N in MAM season, particularly during the night and morning hours. The CASS Savannah, Sudano, and Sahel zones are characterized by surface easterly winds, particularly during the day and evening hours. Moisture flux convergence dominated the Nigeria-Cameroon boundary axis at all times of the day, in Sierra Leone rainforest zone during night and morning hours, and in the eastern axis of the of the CASS Savannah during morning and day time hours. Extremely weaker convergence and divergence are observed in the Sudano and Sahel zones.

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