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RESEARCH ARTICLE

Assessing the Relationship between GNSS-Derived Precipitable Water Vapour and Rainfall Trend in Nigeria

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Abstract

Understanding the relationship between Precipitable Water Vapour (PWV) and rainfall intensity is essential for improving climate modeling, weather forecasting, and water resource management. This study explores the spatiotemporal and seasonal variability of PWV and its correlation with rainfall across Nigeria's diverse climatic zones using GNSS-derived PWV and rainfall data from 2011 to 2016. A strong PWV–rainfall correlation is observed in the arid northern regions, especially in the Sudan/Sahel zone, where elevated atmospheric moisture content aligns with increased rainfall intensity. Conversely, in the Mangrove and Evergreen regions, high PWV levels do not consistently result in significant rainfall, implying the influence of additional meteorological factors such as convection dynamics and local circulations. Seasonally, the study reveals a delayed decrease in PWV during the post-monsoon period in coastal areas, indicating extended atmospheric moisture retention that supports lingering cloud cover and prolonged precipitation. In contrast, northern regions exhibit a rapid decline in PWV, marking a swift transition into dry conditions. Spatially, PWV varies between 0–85 mm in the Arid and Mangrove belts and 0–200 mm in the Wet and Dry Monsoon regions. These variations are shaped by proximity to moisture sources, topography, and prevailing wind systems. Rainfall distribution follows a clear coastal-to-inland gradient. The findings have critical implications for climate adaptation, agricultural planning, disaster risk reduction, and water resource sustainability. By deepening our understanding of atmospheric moisture dynamics, this study supports efforts to enhance food security, manage hydrological systems effectively, and strengthen climate resilience across Nigeria.

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1.0 INTRODUCTION

The continuous adverse impact of the persistent rise in global climate change has remained a major pointer for investigative studies that can help to understand its dynamics to improve preparedness and management strategies. The greenhouse gases have remained a major driver of this global menace but the chief among them is the atmospheric water vapour which acts as the weather engine (Trent *et al*., 2023; Trzcina *et al*., 2023). Water vapour is a dynamic naturally occurring gas in the Earth's atmosphere, composed of molecules of water in the gaseous state. It is an important component of the Earth's climate system, playing a significant role in the regulation of temperature and precipitation patterns because of its high ability to trap heat energy and solar radiation (Loubere, 2012; Yao *et al.,* 2017; Yufeng *et al*., 2018; Nowack *et al*., 2023). Its spatiotemporal content in the atmosphere affects the entire thermodynamics of the atmosphere, thus influencing different meteorological occurrences and severe weather events (Trzcina and Rohm, 2019). The accurate mapping of this critical driver of atmospheric dynamics will significantly enhance our understanding of ongoing climate change and aid in better preparedness for severe weather events.

The Precipitable Water Vapour (PWV), which is the volume of water that would condense if a column of water vapour rising to the top of the atmosphere were to condense over a defined area of space, has been identified to be a principal measure in aiding the understanding of how the atmospheric components over a geographical location can influence local climate of such region (Kuttippurath *et al*., 2023). Several conventional remote sensing techniques including radiosondes and microwave radiometers have been adopted for in situ measurement of the variability of the PWV in the atmosphere. However, the Global Navigation Satellite Systems (GNSS) approach has been proven to be more reliable as it provides a better temporal resolution at comparably better cost with consistent accuracy under all weather conditions (Bevis *et al*., 1992; Bevis *et al*., 1994; Bosy *et al*., 2012; Shi *et al*., 2015; Isioye *et al*., 2017; Yao *et al*., 2017). Though the advent of GNSS is for positioning, mapping, navigation, and timing, incorporating its observations with surface meteorological variables has made it very viable in acquiring spatiotemporal atmospheric water vapour content suitable for meteorological research and applications (Rocken *et al*., 1994; Isioye *et al*., 2016).

Bevis *et al*., (1992) was the first attempt to explore the use of GNSS meteorology for deriving Precipitable Water Vapour (PWV) showing its advantage over other methods. Benevides *et al*., (2015) included the GNSS-derived PWV in rainfall nowcasting at Lisbon Portugal and found it to positively correlate with hourly time lag. On a global scale, GNSS–derived PWV has a high correlation with temperature anomalies and sea height variation, and it decreases as the latitude increases (Chen *et al*., 2022). Several studies have shown that the evolution of rainfall has a peculiar PWV signature which has been successfully deployed for studying severe rainfall events, data assimilation and calibration of numerical weather models, drought detections, climate monitoring, rainfall nowcasting and air quality issues (Isioye *et al*., 2015; Manning *et al*., 2012; Suparta and Zainudin, 2015; Jiang *et al*., 2016; Yao *et al*., 2017; Manandhar *et al*., 2019; Wen *et al*., 2020; Zhu *et al*., 2021).

Kawase *et al*., (2006) identified that PWV is a reliable variable in rainfall forecasting for a hilly geographical location. Yuan *et al*., (2014) successfully deployed water vapour content in the atmosphere to carry out short-term precipitation forecasting. In the temperate climatic environment, Benevide *et al*., (2019) employed this for rainfall nowcasting in Lisbon, Portugal, and Łoś *et al*. (2020) did the same in Poland. In the tropical region, Manandhar *et al*. (2019); Liu *et al*., (2019); Biswas *et al*. (2021), among others, have also successfully deployed this relationship for nowcasting, recording success in rainfall prediction of up to 80 – 96% (Sreeja and Priya, 2022). The application of PWV in rainfall modelling was based on the fact that observed PWV experienced a unique increase in value just before the rainfall event and decreased after the rainfall (Yao *et al*., 2017). It is noteworthy that not all rises in PWV will always lead to rainfall as other thermodynamic variables like temperature, pressures, relative humidity, and others also contribute to rainfall formation (Shoji, 2013; Liu *et al*., 2025).

As the retrieval of GNSS-derived PWV begins to gain research attention in the African continent, Nigeria, among several nations, is at the forefront of engaging this technology (Isioye *et al*., 2017; Osah *et al*., 2021). Isioye *et al*. (2017) demonstrated that diurnal and seasonal GNSS–derived PWV over Nigeria can model the country's seasonal climate and thus can be employed for weather forecasting and nowcasting in Nigeria. Mayaki *et al*. (2018) showed that the Zenith Tropospheric Delay (ZTD) derived over the Nigeria Ground-based GNSS Network (NIGNET) Continuously Operating Reference Stations (CORS) can be transformed into integrated water vapour, which could enhance the study of the precipitation trend in Nigeria if the NIGNET infrastructure is well maintained and administered. Swaffiyudeen *et al*. (2021) modelled the PWV over Nigeria and found that the spatiotemporal variability of PWV across Nigeria is a function of geographical location and seasons.

Bala (2022) identified from analysis of ZTD values derived from Precise Point Positioning (PPP) ZTD over NIGNET stations that the ZTD values for each location can be used to investigate the rainfall pattern in the area. Though all these studies have identified the potential of modelling rainfall with a product of GNSS observations, particularly in Nigeria, none of the studies has conducted the seasonal analysis of PWV over NIGNET to explore its correlation with rainfall trends in Nigeria.

This study investigates the hourly spatiotemporal correlation of the GNSS-derived PWV over the NIGNET with seasonal rainfall events to identify the interrelationships between PWV distribution and rainfall trends. This represents a significant contribution to the United Nations (UN) Sustainable Development Goals, as it offers an overview of the dynamics of rainfall trends in Nigeria, aligning with efforts in climate change mitigation, adaptation, impact reduction through early warning systems, and the preservation of biodiversity on land.

2.0 MATERIALS AND METHODS

2.1 Study Area

Nigeria, located in West Africa, is the most populous Black nation with over 225 million people and a growth rate of 2.78%. It boasts diverse geographical features such as a long coastline, savannas, rainforests, plateaus, and the River Niger, which is a vital element in both its geography and economy. The country's ecosystems, including mangroves and wetlands, house rich biodiversity. Unique climatic seasons are experienced across its regions, with a dry (harmattan) season from November to March marked by Sahara desert winds and a rainy season from April to October, promoting lush vegetation. The transition from long to short rain campaigns occurs in August in the South. Rainfall varies from 500mm in the North to over 3000mm in the South, with coastal states like Bayelsa, and Rivers experiencing the highest. The country is currently grappling with the impact of global climate change on its rainfall patterns, necessitating vigilant monitoring of rainfall events and the need for preparedness for severe weather phenomena.

2.2 Data

The datasets used for the purpose of this study are the GNSS observations acquired from the Nigerian GNSS Reference Network (NIGNET) online database, managed by the Office of the Surveyor General of the Federation, and the hourly rainfall intensity downloaded from the online repository of the Center for Hydrometeorology and Remote Sensing (CHRS). The GNSS-derived PWV from the NIGNET observation has been established to have sufficient accuracy for GNSS meteorology in several studies (Isioye *et al*., 2017; Mayaki *et al*., 2018, Ayodele *et al*., 2020; Swaffiyudeen *et al*., 2021, Bala, 2022). Table 1 summarizes the formats in which they were acquired and the temporal coverage of the datasets.

Table 1: Study Dataset

Datasets	Format	Sources	Application	Temporal coverage
GNSS: Receiver Observation Data	Observation Data in Receiver Independent Exchange Format (RINEX)	Online database of Nigeria GNSS Permanent Reference Network (NIGNET) CORS data and Scripps Orbit and Permanent Array Centre (SOPAC)	Used for GNSS post-processing in GAPS	(6 years) 2011 – 2016
Rainfall Data	Comma-separated values (CSV) were obtained for each geographical location	Online database of the Center for Hydrometeorology and Remote Sensing (CHRS) of the University of California, Irvine.	Use for rainfall trend analysis and assessment	(6 years) 2011 – 2016

The mode of acquisition of the GNSS observation has been discussed extensively in Ojegbile *et al.,* (2023) and Table 2 describes the geographical locations of the selected NIGNET stations.

Table 2: Location of NIGNET CORS selected in this study

S/N	Station Name	Latitude (^{O})	Longitude (^{O})	Height (m)	Located City
1	ABUZ	11.15	7.65	705.06	Zaria
2	BKFP	12.47	4.23	250.00	Birni – Kebbi
3	CLBR	4.95	8.35	57.17	Calabar
4	FUTY	9.35	12.50	247.40	Yola
5	OSGF	9.03	7.49	532.64	Abuja
6	ULAG	6.52	3.40	44.56	Lagos
7	UNEC	6.42	7.50	254.40	Enugu

The PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) system developed by the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine (UCI) employs a neural network-based classification and approximation module to estimate rainfall rates at a spatial resolution of 0.25° × 0.25°, using infrared brightness temperature imagery obtained from geostationary satellites (Hsu *et al.,* 1997; Nyuden *et al.,* 2019; see also https://chrsdata.eng.uci.edu/). In Nigeria, the PERSIANN rainfall dataset has been found to be good enough for hydrological modeling, flood risk mapping, and agricultural planning as it provides long-term rainfall insight and has been extensively used for rainfall studies (Fadipe and Izinyon, 2020; Ganiyu *et al.,* 2025). The temporal and spatial resolution of the secondary datasets used in this study are presented in Table 3.

Table 3: Characteristics of the secondary datasets used in this study

S/N	Dataset	Temporal Resolution	Spatial resolution	Temporal coverage	Year of acquisition
1	GPT3	Hourly	1° by 1°	2011 – 2016	2021
2	PERSIANN Rainfall	Hourly	0.25° by 0.25°	2011 – 2016	2021

2.3 Methodology

The daily observations of the CORS in the NIGNET, captured in 30-second logging intervals for all the stations used in this study, were imported into the GNSS Analysis and Processing Software (GAPS) for observations ranging from 2011 to 2016. GAPS was configured in static mode to use its Precise Point Positioning processing for observations in the form of ionospheric-free linear combinations, incorporating undifferenced L1 and L2 carrier phases, along with pseudo-range measurements from GPS. The 30-second clock products were applied in a sequential least-squares filter. GAPS used Vienna Mapping Functions 1 (VMF1) by Boehm *et al*., (2006) as the a priori hydrostatic delay model and mapping function, with an elevation angle cut-off set at 10 degrees. Corrections were made for phase centre offsets and variations in both satellites' and receivers' antennae by inputting the receiver heights relative to the antenna reference point and the antenna type which aid the GAPS processing system to automatically recalibrate to International GNSS Service Antenna Exchange format. Station coordinates were derived using the International Terrestrial Reference Frame (ITRF) 2008 solution and ambiguities were estimated as real numbers. Other products of the PPP processing include the ZTD and horizontal gradients as detailed in Ojegbile *et al*., (2023). The estimated ZTD values were consolidated from 30-second intervals into hourly averages using a custom MATLAB code developed specifically for this purpose.

A MATLAB subroutine was also downloaded from the data server of the Vienna Mapping Function 3, (https://vmf.geo.tuwien.ac.at/), hosted by the Department of Geodesy and Geoinformation, University of Vienna, and used to empirically extract the surface temperature, $\boldsymbol{T_s}$, mean weighted temperature, $\boldsymbol{T_m}$, surface pressure, $\boldsymbol{P_s}$ from the empirical GPT 3 model following Equation 1 as stated by Landskron and Bohm (2018).

$$\boldsymbol{r(t) = A_o + A_1 cos\left(\frac{doy}{365.25} \times 2\pi\right) + B_1 sin\left(\frac{doy}{365.25} \times 2\pi\right) + A_2 cos\left(\frac{doy}{365.25} \times 4\pi\right) + B_2 sin\left(\frac{doy}{365.25} \times 4\pi\right)} \tag{1}$$

Following that A_o represents the mean value, A_1 and B_1 the annual amplitudes and A_2 and B_2 the semi-annual amplitudes of the parameters being derived for a given time in the year referred to as doy.

The conversion factor $\boldsymbol{\Pi}$ was adopted from Isioye *et al.,* (2017), as given in Equation 2, which is a function of surface temperatures for geodetic application in Nigeria

$$\boldsymbol{\Pi = \left(\frac{0.5245T_s + 132.12}{0.0053499T_s + 1739.07624}\right)} \tag{2}$$

The PWV was then computed from the estimated GNSS-derived Zenith Wet Delay (ZWD) and the meteorological parameter derived from GPT3, following Equation 2 as derived by Bevis *et al.,* (1992) for GNSS meteorology.

$$PWV = \Pi \times ZWD \tag{3}$$

With ZWD in millimetres, the PWV was derived for all the aforementioned stations in millimetres.
The temporal plots of the PWV and rainfall were produced in the MATLAB environment while the spatial distribution of PWV and rainfall intensity were mapped using GIS-based inverse distance weighted (IDW) interpolation within ArcGIS 10.8.1. IDW was selected as the interpolation method due to its computational efficiency and ease of interpretation. The technique estimates unknown values at a given location by weighting observed values from surrounding points based on their inverse-distance relationship.

3.0 RESULTS

3.1 Spatiotemporal variation of PWV and Rainfall

The temporal plots of the variability of PWV and rainfall intensity from Figure 1, 2 and 3 show that each year starts with the dry season (January and February) where the PWV values are also very low. During the rainy season, the PWV values increase progressively till they get to the maximum during the peak of the wet season and retrogress in the same way till November/December when the dry season arrives with the continental wind as harmattan from the Sahara desert. Hence, these seasonal plots of the variability of PWV are significantly related to the rainfall trend over the entire region with unique perturbations during the peak of the rainy season. The gaps in these PWV temporal plots are due to the missing data during the period as identified by Ayodele *et al.,* (2019).

In Figures 1a – c, the pattern of the PWV variability during the rainfall events for the Sudan/Sahel climatic belt for Zaria, Kebbi and Yola locations respectively, there is perturbation of the lowest values of the PWV at the beginning of the year (January/February) and towards its ending (November/November). The peak of the rainy season (May to August) was also found to have the peak values of PWV. Figure 2 a and b representing the temporal pattern of the PWV variability during the rainy season in the Guinea Savanna (Abuja and Enugu) shows the same fluctuation of PWV during the wet season with little or no perturbation in the dry season. At the location in Tropical Wet/Dry Monsoon climatic belt with the highest PWV values in the entire region, Figure 3 (Lagos and Calabar) shows high perturbations during the heavy rainfall pattern in this zone. This is peculiar as this region has a long duration of rainfall and highest tendencies for continuous heavy downpour.

The above spatiotemporal variation of PWV and rainfall provides critical insights into atmospheric moisture dynamics and their influence on precipitation patterns (Ojegbile *et al*., 2023; Pan *et al*., 2024). PWV, which represents the total columnar water vapour in the atmosphere, is a key driver of rainfall formation and intensity (Ferreira and Gimeno, 2024). Understanding its variability across time and space is essential for comprehending regional hydrological cycles, particularly in areas like Nigeria, where rainfall exhibits significant seasonal and spatial heterogeneity (Akinsanola & Ogunjobi, 2017; Olawale *et al*., 2024). These results present the intricate relationships between PWV and rainfall, analysing their temporal trends, spatial distributions and interactions. This nature of the investigation is vital for improving weather prediction, enhancing climate resilience, and addressing challenges associated with climate change impacts on water resources and ecosystems (Ojegbile *et al*., 2023; Kingra & Kukal, 2024; Li *et al*., 2024; Pipatsitee *et al*., 2024; Wang *et al*., 2024).

The hourly variabilities of PWV and rainfall intensity in spatial patterns and temporal trends, as influenced by Nigeria's diverse climatic zones—ranging from the arid Tropical Sudan to the humid Tropical Wet and Dry regions is analysed. Spatially, PWV distribution is influenced by factors such as proximity to moisture sources, topography, and prevailing wind systems, while rainfall exhibits distinct gradients from the coastal to inland regions. Temporally, variations are explored across seasons (DJF, MAM, JJA, SON). Seasonal patterns highlight the transition between wet and dry periods, revealing how PWV accumulation aligns with rainfall intensity and frequency. This will serve as the foundation for further exploration of how PWV interacts with rainfall events and how seasonal dynamics modulate this relationship across Nigeria's diverse climatic landscape.

Generally, the characterization of the PWV variabilities in all the locations showed that the rainy season corresponds to a noticeable increase and peak in PWV values.

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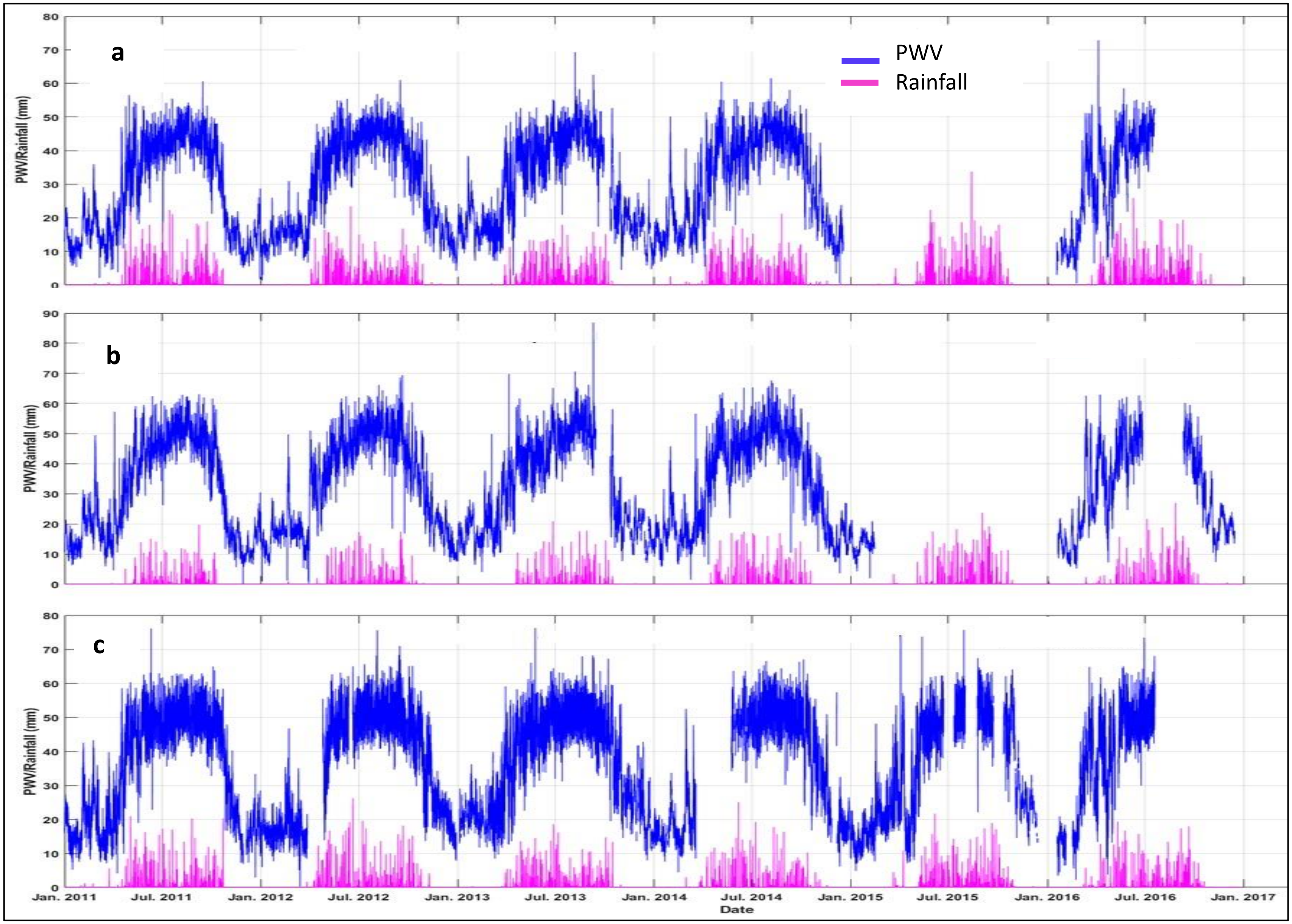

Figure 1: Temporal variability of PWV and rainfall in the Sudan/Sahel climatic belt. **a** - Zaria; **b** - Kebbi and **c** - Yola.

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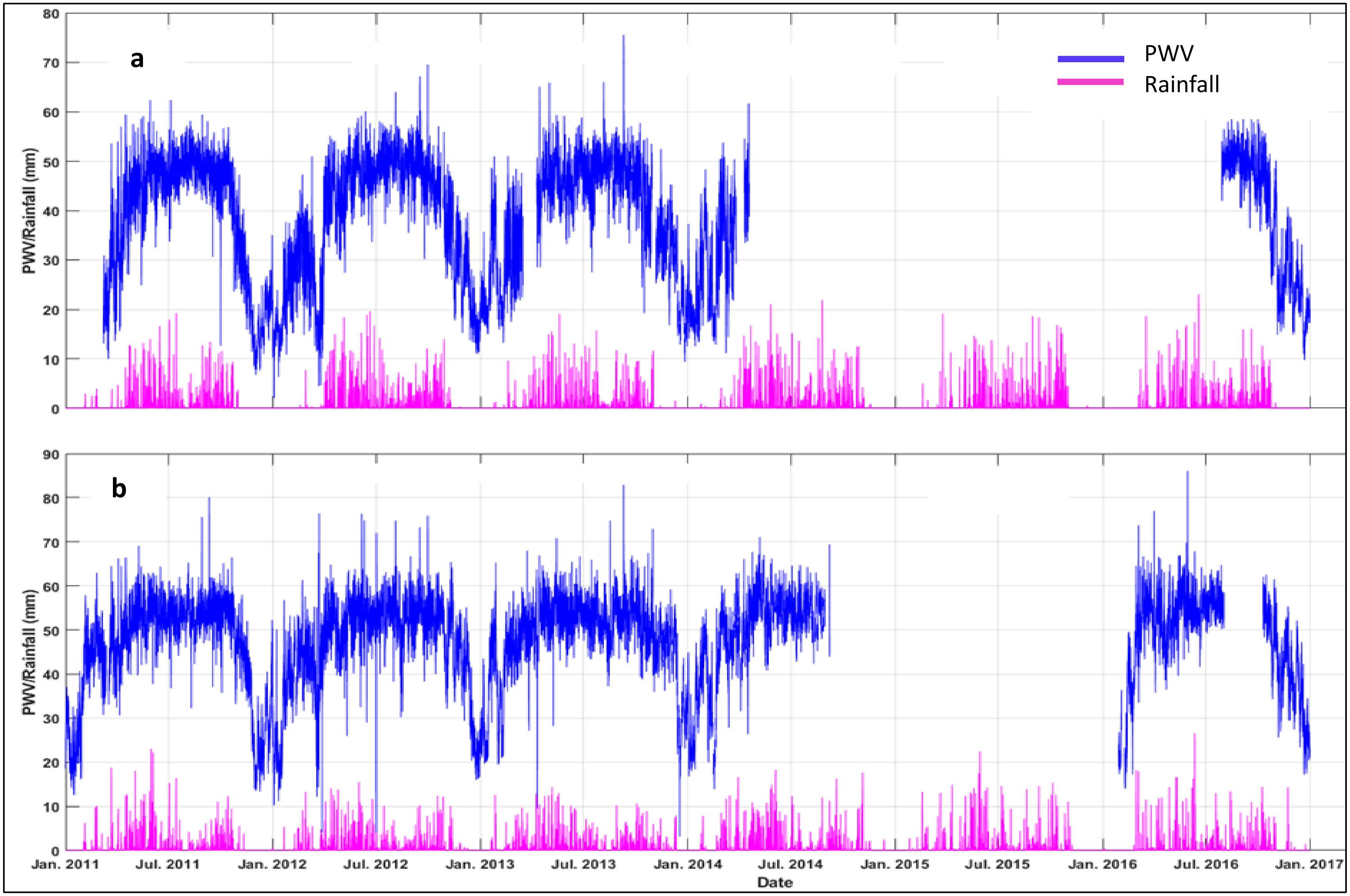

Figure 2: Temporal variability of PWV and rainfall in the Guinea Savanna climatic belt. **a** - Abuja and **b** - Enugu.

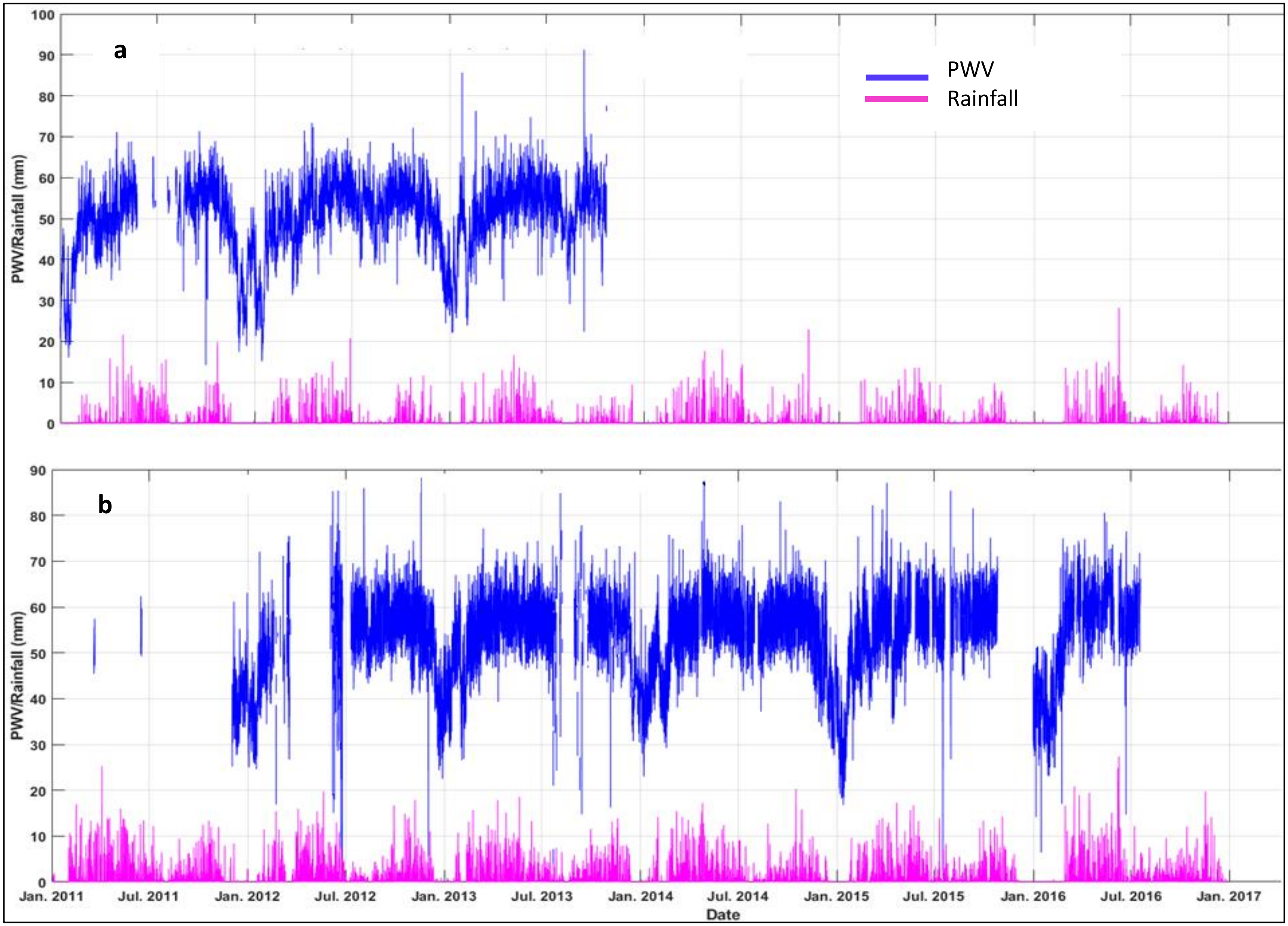

Figure 3: Temporal variability of PWV and rainfall in the Wet and Dry/Monsoon climatic belt. **a** – Lagos and **b** – Calabar

In the case of location in Yola, the PWV time series plot consistently reached its maximum values in July and August in this study. This aligns with previous research findings indicating the peak of rainfall in the region (Sadiq, 2020 and Sadiq *et al*., 2021). The perturbation pattern of PWV at the Abuja location also resonates with the reported period of the height of the rainy season in this location (Adeyemi and Ogolo, 2014). Similarly, what was observed in PWV fluctuations at the Calabar station aligns with the findings of Ewona and Udo (2008), and Ekpe *et al*., (2013).

3.2 Seasonal Maps of PWV and Rainfall Trends in Nigeria

The seasonal variability of the PWV distribution and its relationship with rainfall intensity over a region is crucial to understanding the spatiotemporal trend of the moisture content in the troposphere. Although Nigeria experiences both wet and dry seasons, its unique seasonal variability in rainfall intensity across different regions can be categorized into four annual rainfall campaigns namely: December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON), by previous studies (Ulrich and Babatunde, 2018; Dada, 2019; Tore *et al*., 2022). The MAM period is recognized as the onset of the rainy season in Nigeria, while JJA marks the peak of rainfall. SON represents the gradual retreat of the rains before transitioning into the Harmattan season, characterized by dry, dusty winds from the Sahara Desert, which prevails from December to February (DJF) (Isioye *et al*., 2017).

Figures 4 – 7 present the seasonal maps of PWV and rainfall for these four rainfall campaigns in this study. At the onset of the rainy season (MAM) shown in Figure 4, the PWV values begins to experience a progressive increase, particularly over the Evergreen and Mangrove regions, where moisture begins to accumulate. Rainfall intensity starts to rise, with early-season showers observed primarily in the southern zones. The Middle Belt experiences moderate PWV increments, but this does not immediately translate into substantial rainfall. The Sudan/Sahel region remains relatively dry, indicating a delay in moisture transport from the south.

The peak of the rainy season was observed during the JJA campaign and PWV values reached their highest levels, especially in the Mangrove and Evergreen regions, where monsoonal moisture influx peaks, as seen in Figure 5. Rainfall intensity reaches its maximum in these areas, with substantial precipitation extending into the Middle Belt. The Sudan/Sahel region, despite experiencing a rise in PWV, does not witness an equivalent increase in rainfall due to atmospheric stability constraints. This highlights the uneven relationship between PWV and rainfall across different climate zones.

During SON (Figure 6), PWV levels gradually decline as the monsoon weakens. The Mangrove and Evergreen regions retain relatively high moisture levels, resulting in lingering rainfall. The Middle Belt experiences a slower decline in PWV and precipitation, suggesting a residual moisture effect. The Sudan/Sahel region sees a rapid decrease in PWV, reinforcing its characteristic arid transition into the dry season. This season serves as a critical transition phase, balancing between the wet and dry periods.
The dry season, i.e., DJF (Figure 7) is characterized by the lowest PWV values across all regions, with the most significant reductions observed in the Sudan/Sahel zone. Rainfall is minimal, with only traces present in the Mangrove and Evergreen regions. The dominance of Harmattan winds suppresses atmospheric moisture, limiting precipitation. However, coastal areas such as Calabar and Lagos retain slightly higher PWV levels compared to inland regions, though without substantial rainfall.

In general, there is unique regional variations in PWV and rainfall trends across Nigeria. The Mangrove region, encompassing cities like Calabar and Lagos, consistently exhibits the highest PWV values throughout the year, correlating with persistent rainfall patterns. The Evergreen region, spanning parts of the Middle Belt, follows a similar trend but with greater seasonal variability. Conversely, the Sudan/Sahel region demonstrates the lowest PWV levels and the most pronounced dry-season effects, limiting rainfall occurrence. The Middle Belt acts as a transitional zone between the humid south and arid north, with moderate seasonal PWV variations. During JJA, a significant increase in both PWV and rainfall is observed, whereas the SON season shows a more gradual moisture reduction compared to the northern regions. This region also exhibits variability in PWV - rainfall which may be due to the interaction of localized convection and topographic influences.

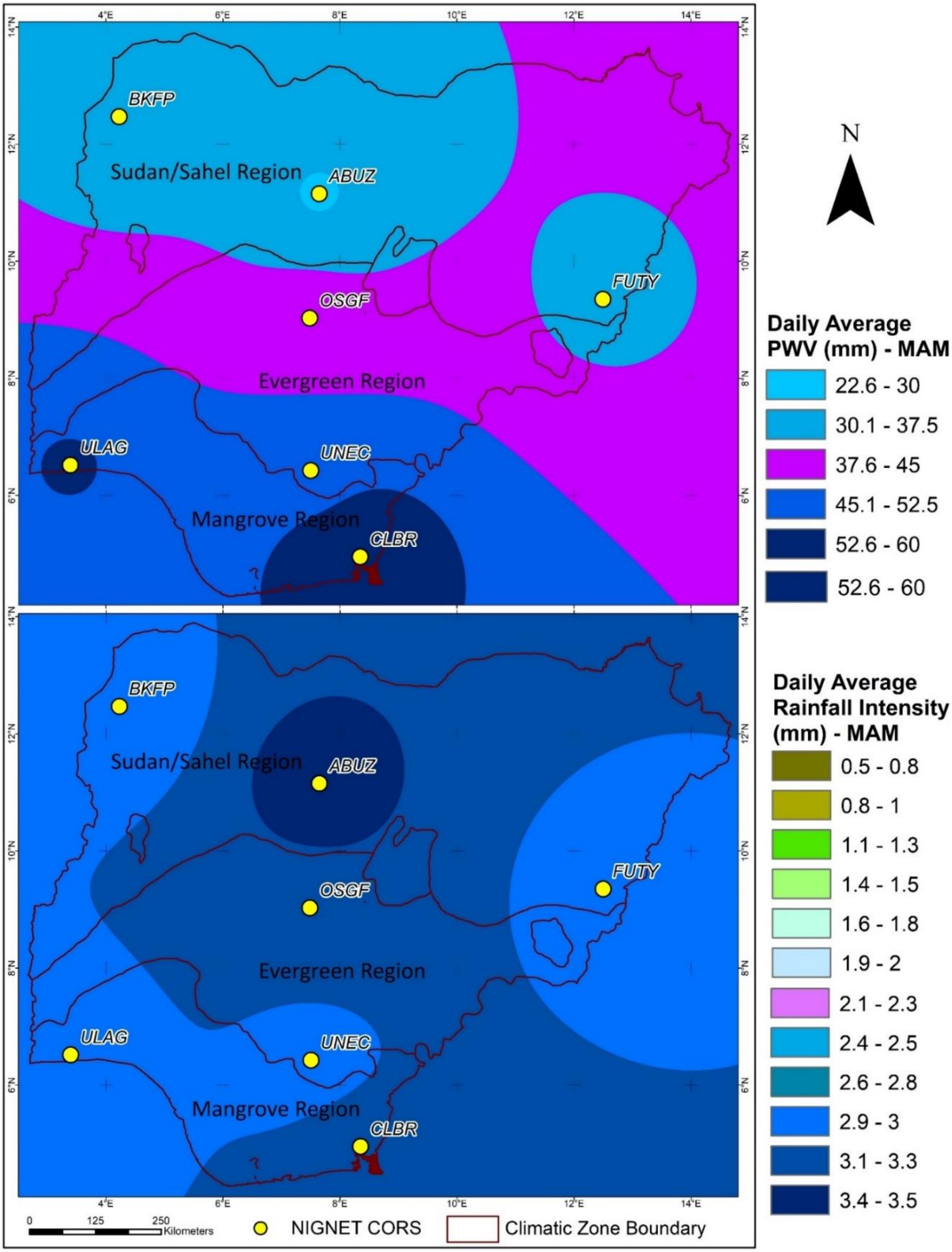

Figure 4: Spatial variation of PWV and rainfall intensity in Nigeria at the onset of the rainy season

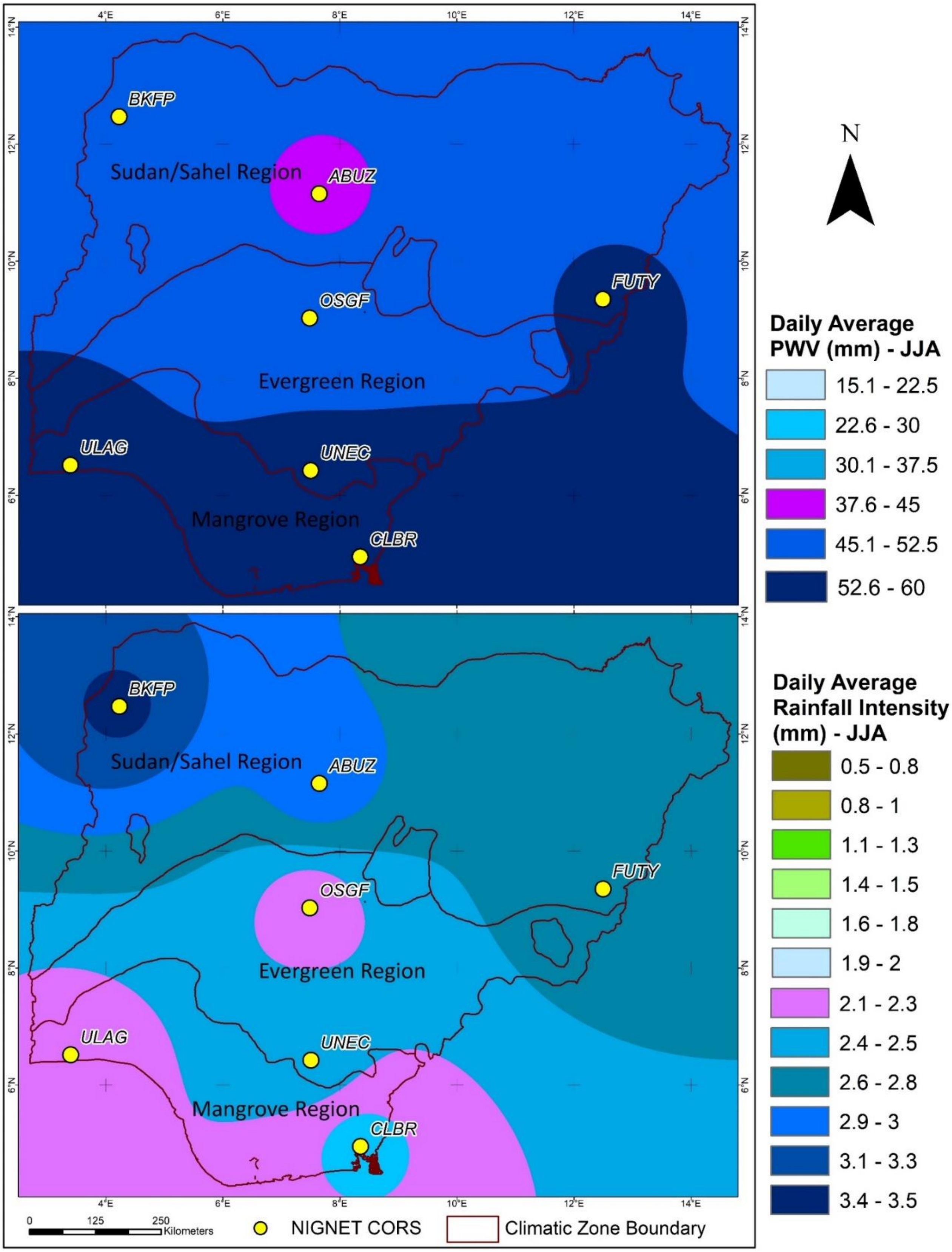

Figure 5: Spatial variation of PWV and rainfall intensity in Nigeria at the peak of the rainy season

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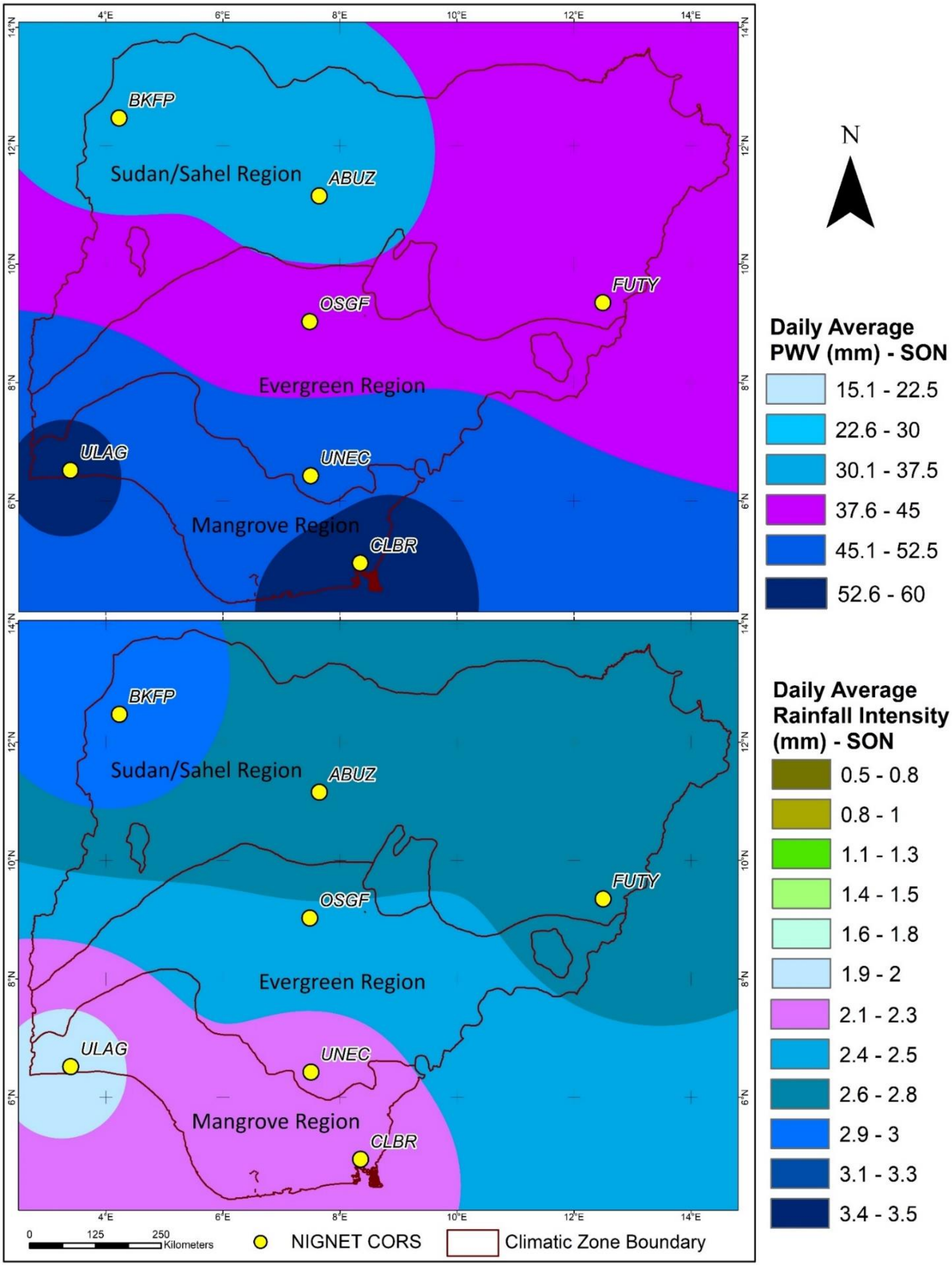

Figure 6: Spatial variation of PWV and rainfall intensity in Nigeria towards the end of the rainy season

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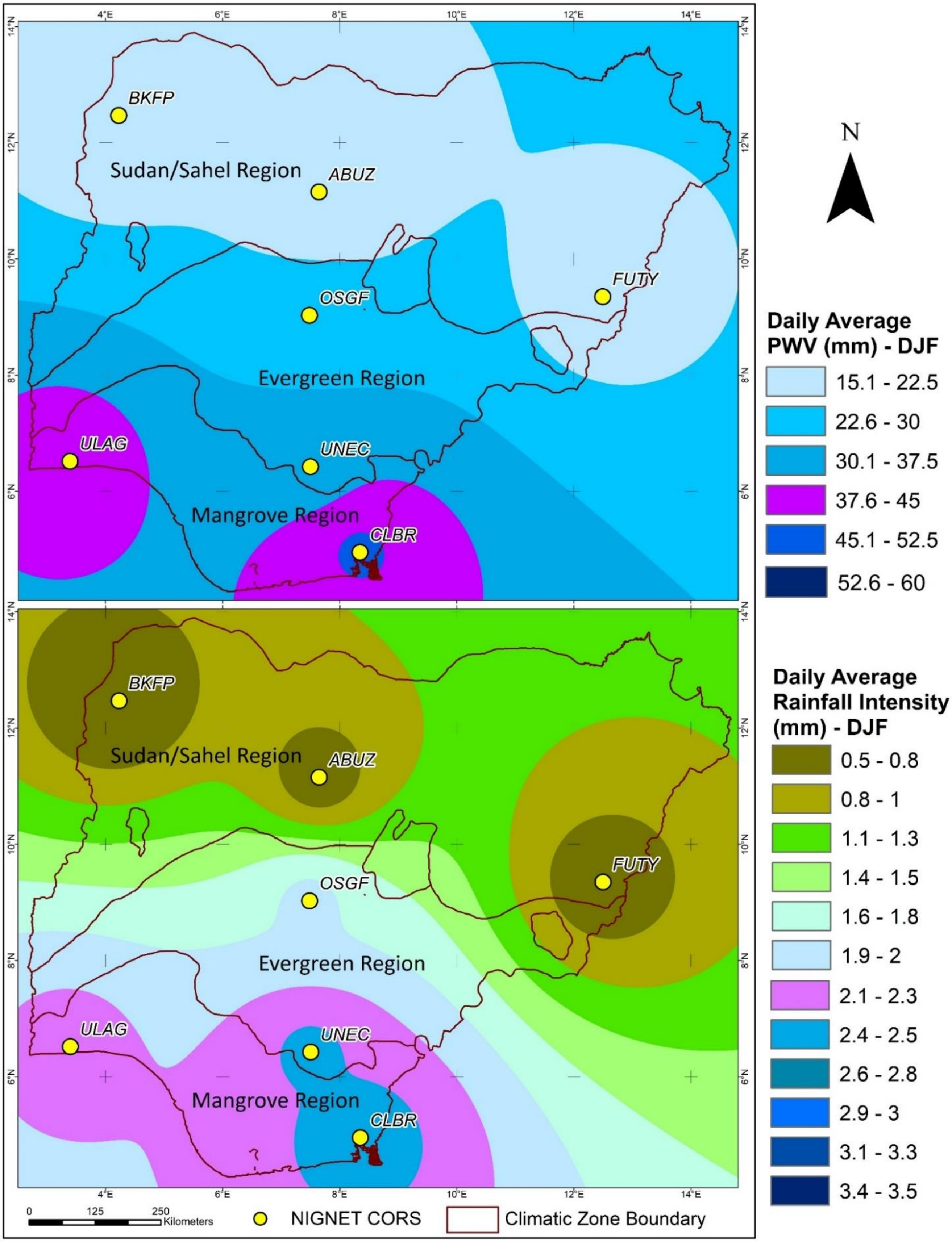

Figure 7: Spatial variation of PWV and rainfall intensity in Nigeria during the dry season

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3.3 Relationship between PWV and Rainfall Events in Nigeria

The peculiar signature of the PWV-rainfall interaction varies across the different climatic regions and seasons in Nigeria. This section presents the correlative trend of the spatial and temporal variations in PWV and their coherence with rainfall events, in order to provide insights into how moisture availability influences precipitation patterns across different locations.

Table 4 presents the seasonal mean and standard deviation (SD) of Precipitable Water Vapour (PWV) across Tropical Sudan, Guinea, and Wet and Dry/Monsoon climatic belts. A clear seasonal variation is evident with PWV reaching its peak during the wet season (JJA) and dropping to its lowest levels in the dry season (DJF). The variability in PWV across these climatic zones reflects the influence of regional atmospheric circulation and moisture availability in the Nigeria troposphere, throughout the year.

Table 4: Seasonal PWV Variability across Climatic Zones

Climatic Zone	DJF		MAM		JJA		SON	
	Mean (mm)	SD (mm)	Mean (mm)	SD (mm)	Mean (mm)	SD (mm)	Mean (mm)	SD (mm)
Tropical Sudan	15.62	5.22	29.45	11.13	43.28	4.60	31.04	12.17
Tropical Guinea	25.17	8.71	39.15	9.63	48.61	3.62	40.14	10.37
Tropical Wet and Dry / Monsoon	41.54	9.80	52.89	5.33	54.37	5.42	54.02	5.51

The DJF season which corresponds to the peak of the dry season, records the lowest PWV values across all climatic zones. The Tropical Sudan zone has the least atmospheric moisture (15.62 mm), while the Tropical Wet and Dry zone maintains the highest levels (41.54 mm). As the MAM season (March–May) approaches, PWV increases across all zones, with values rising to 29.45 mm in Tropical Sudan, 39.15 mm in Tropical Guinea, and 52.89 mm in Tropical Wet and Dry, marking the transition into the rainy season. During the JJA season (June–August), PWV reaches its maximum levels, with all zones experiencing peak atmospheric moisture content. The Tropical Wet and Dry zone records the highest PWV (54.37 mm), followed by Tropical Guinea (48.61 mm) and Tropical Sudan (43.28 mm). This reflects the dominance of the monsoon system and increased convective activity during this period. The SON season (September–November) shows a slight decline from JJA values, but PWV remains relatively high, indicating a gradual transition back to drier conditions.

Across all seasons, the Tropical Sudan zone consistently records the lowest PWV values, emphasizing its semi-arid nature. The sharp contrast between its lowest PWV in DJF (15.62 mm) and highest in JJA (43.28 mm) highlights the strong seasonal variability of atmospheric moisture in this region. The Evergreen Guinea zone experiences moderate moisture levels throughout the year. While its PWV values remain lower than those of the Tropical Wet and Dry zone, they still exhibit a clear seasonal trend, increasing from 25.17 mm in DJF to 48.61 mm in JJA. This indicates a more humid environment than the Sudan zone but is still significantly influenced by seasonal changes. With a minimum of 41.54 mm in DJF and a peak of 54.37 mm in JJA, the Wet and Dry/monsoon region retains substantial atmospheric moisture. This region has relatively stable PWV values highlighting its humid climatic characteristics.

The standard deviation (SD) values revealing the extent of PWV fluctuations within each season show that the highest SD values occur in DJF and SON, particularly in the Tropical Sudan zone (5.22 mm and 12.17 mm, respectively) and the Tropical Guinea zone (8.71 mm and 10.37 mm, respectively). This suggests greater variability in atmospheric moisture during transitional periods, influenced by shifts between dry and wet conditions. Conversely, the JJA season exhibits the lowest SD values, especially in the Tropical Guinea zone (3.62 mm) and the Tropical Wet and Dry zone (5.42 mm). The reduced variability in this season indicates stable and consistently high PWV levels, which aligns with the peak monsoon period when sustained moisture influx dominates.

Figures 8 and 9 present the average hourly PWV values and Rainfall Intensity (RI) respectively for each of the locations in used in this study. The Tropical Sudan region exhibits the lowest PWV values across all seasons, with DJF recording the least moisture availability; 15.6 mm per hour in Zaria (ABUZ), 16.7 mm per hour in Kebbi (BKFP) and 19.4 mm per hour in Yola (FUTY). This directly correlates with the low rainfall intensity observed during the same period (0.5–0.6 mm/hour). PWV and rainfall intensity gradually increase into MAM, peaking in JJA (43.3 mm per hour in ABUZ, 48.9 mm per hour in BKFP, and 52.8 mm per hour in FUTY), the main wet season, where the highest rainfall intensity is recorded (up to 3.3 mm/hour in BKFP). SON shows a slight decline, signalling the transition into the drier months.

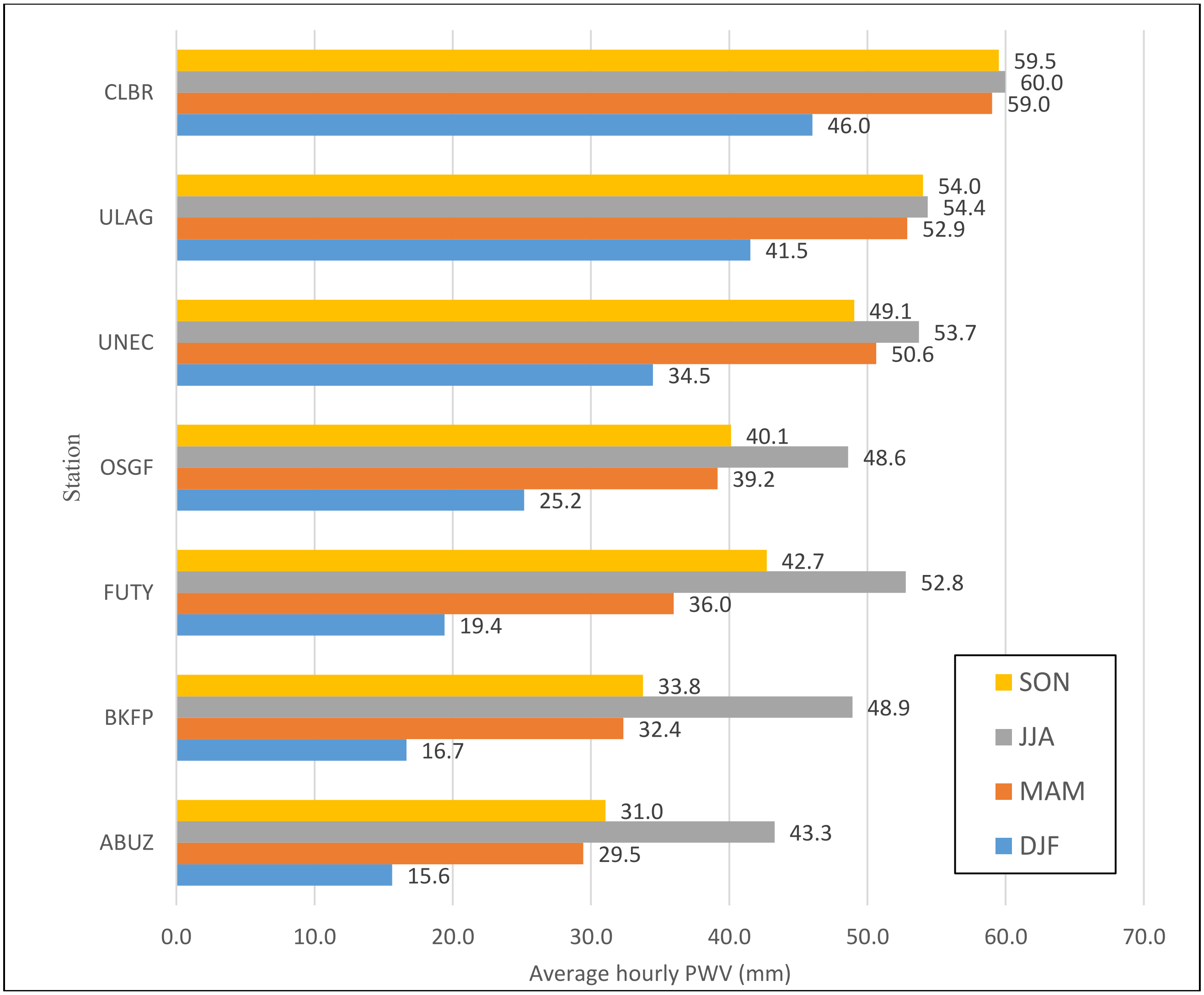

Figure 8: Average hourly PWV across the climatic zones

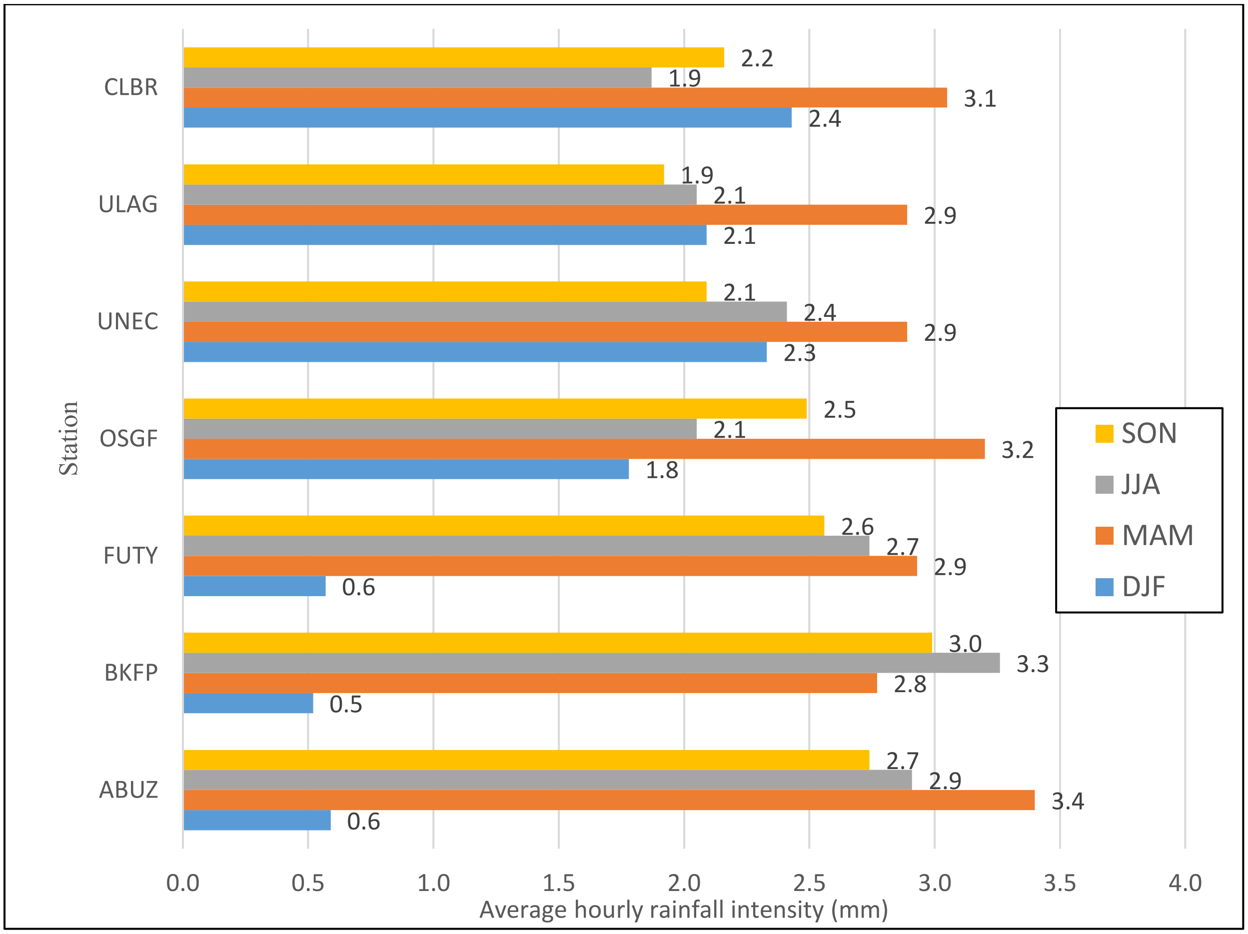

Figure 9: Average hourly rainfall intensity across the climatic zones

The Tropical Guinea zone displays higher overall PWV levels than the Sudan region, with JJA (48.6 mm per hour in OSGF, 49.1 mm per hour in UNEC) maintaining peak moisture content. DJF remains the driest season but has higher moisture than Sudan, with 25.2 mm per hour (OSGF) and 34.5 mm per hour (UNEC). Rainfall intensity follows a slightly different pattern, with significant values in both MAM and JJA, especially in OSGF, where MAM rainfall intensity (3.2 mm/hour) surpasses JJA (2.1 mm/hour). This suggests an earlier onset of the rainy season in this region compared to Sudan.

ULAG and CLBR, both in the Tropical Wet and Dry region, exhibit the highest PWV values across all seasons. Even in DJF, when most other regions experience a significant drop in moisture, these stations record 41.5 mm per hour (ULAG) and 46.0 mm per hour (CLBR). Peak values occur in JJA and SON, with CLBR reaching 60.0 mm per hour in JJA. This persistent high PWV aligns with the rainfall intensity trends, where MAM experiences the highest rainfall intensity (3.1 mm/day in CLBR, 2.9 mm/day in ULAG). Unlike other regions where JJA dominates rainfall, here, rainfall is relatively well-distributed across MAM, JJA, and SON, making this zone the most stable in terms of moisture and precipitation. These highlight the significant role of climatic zones and seasonal cycles in modulating atmospheric water vapour in Nigeria, crucial for understanding rainfall patterns and hydrological processes.

The correlation plot (Figure 10) further elaborates the relationship between Precipitable Water Vapour (PWV) and rainfall intensity (RI) across various locations. All PWV values from different locations exhibit a very high correlation (0.86–1.00), and at the climatic belts is between 0.98 – 1.00, suggesting that PWV over the Nigeria troposphere is spatially consistent in all the regions. The highest correlations between PWV and rainfall intensity occur in Sudan region, Zaria ABUZ (0.77), Yola FUTY(0.83) and Kebbi BKFP (0.90), indicating that in the Sudan climatic regions, increased PWV has a stronger influence on rainfall events.

Abuja, OSGF (0.3) and Enugu UNEC (0.24), exhibit very weak correlation implying that higher PWV does not necessarily translate to increased rainfall in this region. This suggest that there are interactions of the dry wind from the Sudan Desert and the Monsoon wind coming from the south. The weakest PWV – rainfall correlations was observed in the Wet and Dry climatic belt with Lagos ULAG (0.13) and negative in Calabar CLBR (-0.12). This suggests that for locations in this region, factors other than PWV such as local convection, wind patterns, or other meteorological conditions may play a more dominant role in driving rainfall variability.

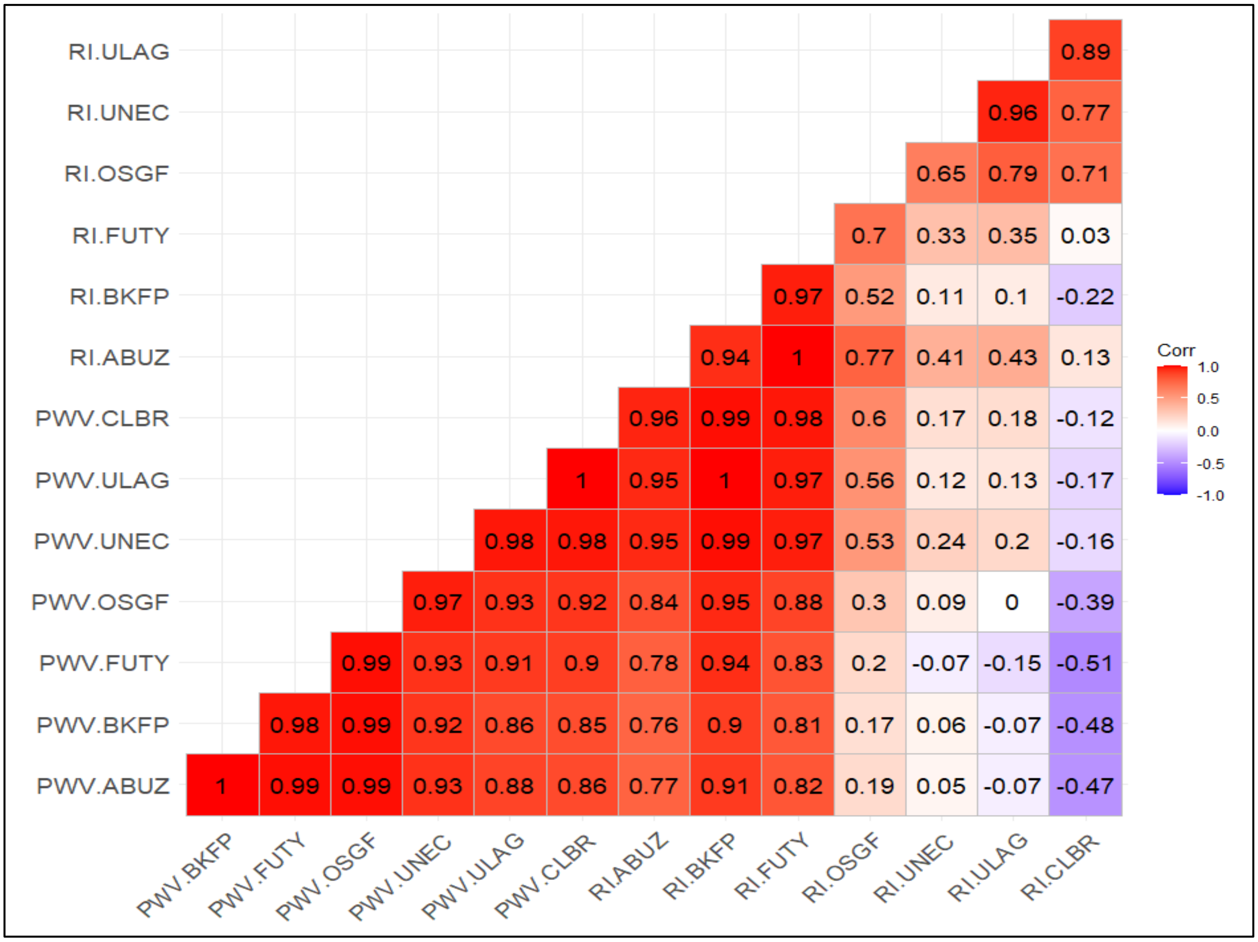

Figure 10: Correlation between PWV values and Rainfall Intensity

The relationship between tropospheric PWV values and extreme rainfall has been shown to vary by location and season (Yao *et al*., 2017; Manandhar *et al*., 2019). Following Arijaje *et al*., (2022), severe instances of precipitation in Nigeria occurs when the rainfall intensity per hour is equal or greater than 10mm per hour. The severe rainfall for the years under consideration in this study was found to be as shown in Table 5.

Table 5: PWV threshold values at instances of severe rainfall

	Tropical Sudan/Sahel			Tropical Savanna Guinea		Tropical Wet and Dry / Monsoon	
	ABUZ	**BKFP**	**FUTY**	**OSGF**	**UNEC**	**ULAG**	**CLBR**
PWV range (mm)	32 - 56	38 - 67	37 - 66	42 - 63	43 - 73	52 - 73	47 - 77

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This result is consistent with the findings of Sreeja and Shejule (2022) who identified global PWV threshold ranges for rainfall modeling and prediction as 0 – 45 mm in temperate regions, 0 – 80 mm in subtropical regions, and 30 – 70 mm in tropical regions.

Studies have established that the relationship between the PWV and rainfall event is positive though increase in PWV values does not necessarily mean rainfall, but a persistent increase in this PWV can be an indication of extreme rainfall especially in tropical regions (Benevides *et al*., 2015; Yao *et al*., 2017; Zhao *et al*., 2020). On investigating the relationship between sub-diurnal variability in GNSS-derived PWV and severe rainfall events in this study at the ULAG station, a notable severe rainfall event occurred in Lagos on 28 June 2012 which was identified to be very catastrophic by Okoye and Ojeh (2015). Figure 11 indicates that the rainfall began gradually around 3:00 pm on Wednesday, 27 June 2012, with increasing intensity into the night. It is noteworthy that the PWV values exceeded the severe rainfall threshold of 52 mm consistently for more than 12 hours indicating a strong potential for heavy rainfall development.

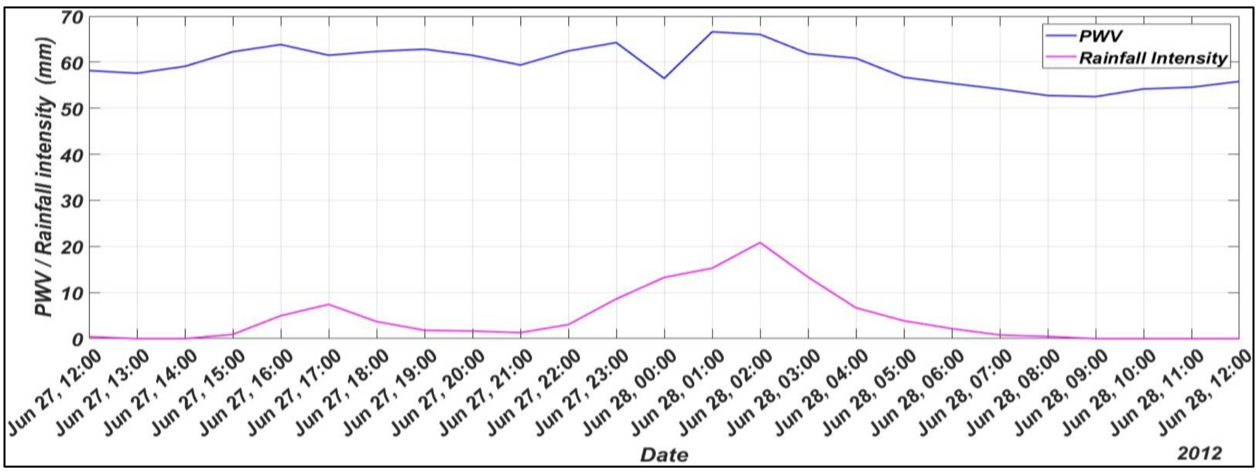

Figure 11: Hourly variability of PWV in Lagos (ULAG) between 27 – 28 June, 2012.

The PWV variability during this period signalled a high likelihood of intense precipitation, but the severe downpour only commenced around 11:00 pm on 27 June and persisted until approximately 4:00 am on Thursday, 28th June, 2012. This was followed by intermittent drizzles which persisted until around 9:00 am on 28th June leaving the entire Lagos metropolis largely flooded (see also https://pmnewsnigeria.com/2012/06/28/heavy-rain-wreaks-havoc-in-lagos-ogun-states/).The devastation caused by the impact of the flooding events could have been averted with the consistent monitoring of the sub-diurnal variability PWV trends because necessary preparedness and early warning system would have been engaged based on such observation system.

4.0 Discussion of Findings

The relationship between Precipitable Water Vapour (PWV) and rainfall in Nigeria exhibits clear spatiotemporal variations, influenced by climate zones, prevailing weather systems, and moisture availability. In the humid southern regions, there is a strong correlation between high PWV and increased rainfall intensity, as moisture-laden air from the Atlantic Ocean supports continuous precipitation. Conversely, in the Sudan/Sahel region, PWV increases do not always correspond to significant rainfall, suggesting that additional meteorological factors, such as convective instability, vertical wind motion, and synoptic-scale circulations, modulate precipitation formation (Adeyewa and Nakamura, 2003; Balogun *et al*., 2019; Omotosho *et al*., 2019).

PWV and rainfall follow a strong seasonal pattern in Nigeria, demonstrating the direct influence of atmospheric moisture availability on precipitation. In the dry season (DJF), PWV levels are at their lowest, particularly in the Sudan/Sahel zone (15 – 20 mm) due to the dominance of dry northeasterly Harmattan winds, leading to minimal rainfall. In contrast, the coastal and rainforest regions retain higher PWV values (~30 – 40 mm), supporting occasional light precipitation. In the transition seasons (MAM and SON) – PWV begins to increase in MAM, initiating the onset of the West African Monsoon, with rainfall intensities rising progressively.

SON exhibits a delayed PWV reduction in the humid southern regions, indicating moisture retention that prolongs light rainfall and cloud formation even after peak rainfall months (Odekunle and Eludoyin, 2014; Odekunle *et al*., 2014). At the prime of the rainy season (JJA), the highest PWV values (50–60 mm in southern Nigeria) occur, aligning with the peak of monsoonal rainfall. The monsoon trough, strong moisture convergence, and convective activity lead to intense and widespread precipitation, particularly in coastal and forest regions (Olaniran, 2018; Nkrumah, 2020).

All the climatic belts in Nigeria exhibit unique PWV and rainfall interactions. Tropical Sudan (ABUZ, BKFP, FUTY), known to be the semi-arid region experiences the lowest PWV values across all seasons, with a sharp decline in moisture after the wet season. Despite occasional PWV increases, rainfall remains limited due to insufficient convective activity and strong dry-air intrusion from the Sahara (Adigun *et al*., 2024). In tropical Guinea (OSGF, UNEC), the transitional zone between arid and humid climates, the PWV value is observed to be moderately higher with small variability in the transition of seasons. The wet season characterized by sustained heavy rainfall has the highest PWV between June and August in this region and a comparable value with the northern region at the onset of the rainy season (MAM) (Adeyeri *et al*., 2020). The Tropical Wet and Dry (ULAG, CLBR) region is the climatic belt with the most abundant moisture content in its troposphere. There is a persistently high PWV greater than 40 mm in the DJF season. Rainfall is more evenly distributed across MAM, JJA, and SON, with strong monsoonal influence ensuring sustained wet conditions throughout the year (Ilesanmi, 2019).

The identified uniqueness of the PWV - rainfall relationship in this study highlights a strong correlation in humid regions and weaker associations in drier zones due to meteorological constraints (Ogunjobi *et al*., 2021). The observed lag effect in moisture reduction in SON emphasizes the role of residual atmospheric moisture in prolonging precipitation, a factor critical for seasonal forecasting and water resource management. The understanding of the dynamics of PWV variations across the climatic region will further enhance flood risk assessment, particularly in southern Nigeria, where prolonged moisture retention could contribute to post-monsoonal flooding. Conversely, in semi-arid regions, the discrepancy between PWV and rainfall highlights the importance of synoptic-scale studies to refine drought prediction models.

5.0 Conclusion

The spatiotemporal and seasonal relationship between the moisture content over the Nigeria troposphere has been assessed in this study to evaluate how the variability of PWV and rainfall intensity correlate so that severe rainfall or drought campaigns that often result from climate change impact can be better prepared for and/or monitored. The variability of GNSS-derived PWV was found to increase down the latitude, least at the arid north and very high at the humid south. Temporally, the seasonal PWV cycle mirrors rainfall distribution, with peak values in JJA (June–August) aligning with the monsoon season and low values in DJF (December–February) corresponding to the dry Harmattan period.

The transitional months (MAM and SON) show moderate moisture variability, with PWV lingering longer in southern coastal regions than in the drier northern zones. This lag in moisture reduction in SON suggests persistent atmospheric moisture that sustains residual rainfall and cloud cover, especially in Mangrove and Evergreen forest zones (Ilori and Ajayi, 2020). The PWV – rainfall correlation in the tropical Sudan region suggests that monitoring the moisture content over that region can aid rainfall monitoring and its influence on flash flooding that has been experienced in this region.

These findings contribute to climate adaptation strategies by providing insights into regional rainfall variability and aiding in precision agriculture, urban planning, and water conservation efforts. Though the correlation of PWV content in the troposphere with rainfall intensity in the presence of other physical climate parameters will give more insight into the drivers of severe rainfall intensity, this study presents a fundamental purview of the nature of moisture content in Nigeria’s troposphere during different seasons. Future work will need to investigate the feature importance of several climate parameters during severe rainfall or drought monitoring in Nigeria from approved data sources. Hence, the moisture content evaluated by the PWV in a location in Nigeria has unique signatures in the different geographic belts in Nigeria and should be adequately investigated to curb the impending menace of the climate change impact on this promising economy.

Author Contributions

Conceptualization - OBM; Development of the concept - OBM, OGO, OEA, JBO, Methodology – OBM, OGO, OEA, JBO, CJO; Data curation – OBM, OGO, OEA, JBO, CJO; Visualisation – OBM, CJO, OGO, OEA, JBO; Results and discussion - OBM, CJO, OGO, OEA, JBO; Writing (original draft, review and editing) – OBM, OGO, OEA, JBO, CJO.

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