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The Dynamics of ERA5 and GNSS-Derived Precipitable Water Vapour in the Climatic Zones of Nigeria

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ABSTRACT

Precipitable water vapour (PWV) is a crucial atmospheric parameter that measures the amount of water vapour in the atmosphere above a specific location. The analysis of PWV variation is required to improve the understanding of climatic variability. The state-of-the-art fifth generation of the European Centre for Medium-Range Weather Forecasts (ERA5) which provides historical PWV records has gained prominence in the research community. The ERA5 dataset requires validation using in-situ ground observations such as Global Navigation Satellite Systems (GNSS). However, there is a limited understanding of the climatic and seasonal variability of ERA5 PWV over Nigeria. The sparse GNSS data coverage in previous studies has also limited their potential for correlating the PWV variations with significant or severe weather occurrences. This study investigates the spatio-temporal and seasonal correlation of ERA5 PWV with the GNSS-derived PWV over Nigeria between 2011 and 2016, using GNSS observations from the Nigerian GNSS Network (NIGNET). The GNSS observations were processed using Precise Point Positioning software to derive the Zenith Tropospheric Delay and its products. Subsequently, the PWV was derived from the Zenith Wet Delay. The quantitative analysis was facilitated using spatial interpolation and statistical metrics. The findings reveal a very close correlation between ERA5 PWV and the GNSS-derived PWV across all climatic regions in Nigeria, with the highest correlations occurring in the Sudan/Sahel region (r: 0.96 - 0.98). In the dry season, there is a decrease in PWV from lower to higher latitudes. During the wet season of 2012 which recorded severe precipitation and flooding, the highest PWV content occurred in the mangrove and evergreen climatic regions located in south-west and south-eastern Nigeria. This study has proven the utility of the ERA5 PWV for mapping and monitoring the water vapour content and for long-term climate studies over Nigeria.

Keywords: Global navigation satellite systems, Precise point positioning, Precipitable water vapour, Severe precipitation, ERA5

1.0. Introduction

Precipitable water vapour (PWV) is a crucial atmospheric parameter that measures the amount of water vapour in the atmosphere above a specific location (Kelsey *et al*., 2022). It represents the depth of water that would result if all the water vapour in a vertical column above that location were condensed and falls as precipitation (Ojrzyńska *et al*., 2022). PWV has a wide range of applications in severe weather forecasting/prediction, climate studies, water resource management, satellite communications, aviation and transportation, environmental studies and disaster monitoring. Thus, the measurement of its spatiotemporal distribution and variation has been a subject of interest in several studies (e.g., Khaniani *et al*., 2021; Wang *et al*., 2022; Dong *et al*., 2023; Pipatsitee *et al*., 2023; Sarkar *et al*., 2023).

The measurement and monitoring of PWV improves the understanding of Earth's atmospheric dynamics and its influence on weather and climate, as well as human activities that are impacted by the content of the atmospheric water budget (Daniela, 2001; Isioye *et al*., 2019). There are several methods for measuring and mapping PWV such as: radiosondes, microwave radiometers, infra–red sensors, light detection and ranging (LiDAR) sensors, and global navigation satellite systems (GNSS). Recently, the practice of deriving PWV from numerical weather prediction models (NWPs) such as the ERA5 dataset has gained wide prominence.

ERA5 is a state-of-the-art global atmospheric reanalysis dataset that contains a comprehensive and consistent record of historical weather and climate variables produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), and launched in July 2017 to succeed the ERA–interim reanalysis (Amangabara and Obenade, 2023). ERA5 is the fifth generation of this kind of dataset from ECMWF and it represents a significant improvement over its predecessors in different ways. Its high temporal and spatial resolution, wide range of variables, and extensive data assimilation make it a valuable resource for researchers and organisations worldwide working on climate and atmospheric science, weather forecasting, and environmental studies (Bosco *et al*., 2020; Ying *et al*, 2022; Li *et al*., 2023; Peng *et al*., 2023).

GNSS is highly regarded as one of the most reliable sources of PWV and has repeatedly outperformed other methods in several studies (Jiang *et al*., 2016; Isioye *et al*., 2017; Shejule and Sreeja, 2022). This is due to its high spatio-temporal resolution, all-weather operability, continuous monitoring, interoperability of datasets, cost-effectiveness and high operational reliability. In Africa, several GNSS reference networks have been established under different initiatives such as the African Geodetic Reference Framework (AFREF) and the Nigerian Geodetic Reference Network (NIGNET). Isioye (2017) demonstrated that NIGNET observations were adequate for GNSS meteorology. Mayaki (2019) used NIGNET observations for deriving GNSS zenith tropospheric delay (ZTD) which were identified to have the potential for climatic studies. In another study using NIGNET, Bawa *et al*. (2021) mapped the PWV over Nigeria using GNSS observations. Bala (2022) also adopted NIGNET data for studying the spatial variation of PWV in Nigeria.

Despite the high reliability and high temporal resolution (data logging interval) of GNSS observations, their sparse distribution in the African continent is a serious limitation and a confounding factor for PWV analysis. In contrast, NWPs such as ERA5 which have a higher spatial resolution enable more robust analysis over wider territories. Moreover, the historical records available for ERA5 are more extensive than most of the recently established GNSS stations. Several studies have assessed the relationship between numerical weather prediction models and GNSS-derived PWV. For example, Nemaoui *et al*. (2017) found the difference between the GNSS-derived PWV and the ERA-interim PWV to be an average of 4.0 mm in Algeria. A handful of studies have assessed the accuracy of the ERA5 dataset in Nigeria and Africa (e.g., Bawa *et al.*, 2022; Nzelibe *et al*., 2023). Abimbola *et al*. (2017) found that the root mean square error (RMSE) of the difference between the GNSS-derived PWV and the National Centre for Environmental Prediction (NCEP) II for three GNSS stations in Nigeria range between to be 3.2 and 9.9mm. Isioye *et al*. (2017) found this difference to be ~ -1.2 mm on daily average over Nigeria for five NIGNET stations. Compared to other numerical weather models, the ERA–interim PWV was found to be superior in terms of the daily, monthly and seasonal variation (Isioye *et al*., 2016; Isioye *et al*., 2017).

The accuracy of long-term reanalysis datasets such as ERA5 varies in different parts of the world and responds to changes in weather and climate. Validating ERA5 measurements in West Africa is a serious challenge due to the sparse coverage of continuously operating GNSS reference stations (CORS) in the region. The seasonal variation of PWV is closely tied to the wet and dry seasons in Nigeria and this often has significant implications for agriculture, water resources, and climate monitoring. Nigeria has distinct wet and dry seasons because of its proximity to the equator and the influence of the West African Monsoon. Significant variations in rainfall, temperature, and atmospheric conditions define these seasons (Ibebuchi and Itohan, 2023). The wet season, typically between April and October is the period the country experiences the West African Monsoon, which brings heavy rainfall (Onafeso, 2023). The West African Monsoon retreats during the dry season, which runs from November to March. This results in lower rainfall and the peculiar harmattan season, which is marked by a dry and dusty trade wind that blows throughout West Africa and originates in the Sahara Desert (Ojigi and Opaluwa, 2019; Kendon *et al*., 2023). Understanding the seasonal variations in PWV has great potential for improved climate resilience and weather forecasting in Nigeria (e.g., Ekpe, 2014; Ojigi and Opaluwa, 2019; Wang *et al*., 2022; Dong *et al*., 2023; Pipatsitee *et al*., 2023).

Despite their modest achievements, several of the existing studies were limited by the spatial and temporal coverage of the datasets. Moreover, the influence of climatic variability on the accuracy of PWV over Nigeria has not yet been holistically investigated. Sayne (2011) opined that "Nigeria's climate is likely to see growing shifts in temperature, rainfall, storms, and sea levels throughout the twenty-first century and poor adaptive responses to these shifts can fuel violent conflict in some areas of the country." A year later (i.e., 2012), severe rainfall among other issues led to serious flooding in 33 states of Nigeria (Ajaero *et al*., 2016).

Thus, a spatiotemporal understanding of the PWV over the nation's troposphere can be a major factor in understanding the dynamics of flooding and other hydrological disasters. The present study addresses the historical analysis of the relationship between ERA5 and GNSS-derived PWV in Nigeria, and the seasonal variations of PWV in various climatic zones of Nigeria.

2.0. Methodology

The workflow diagram of the methodology is shown in Figure 2, and the various stages are discussed in the following sections.

2.1 Study area

Nigeria is geographically situated in the West African tropical region within latitudes 4ºN - 14ºN and longitudes 3ºE - 15ºE, and has a land area of about 910,770 km^2. The country has a vast stretch of coastline along the Gulf of Guinea to the south, vast savannas, dense rainforests, plateaus, and a central belt of hills and mountains, among other diverse geographical features. Important geological features include the northeastern Chad Basin and the Central Benue Trough. Nigeria's diverse ecosystems, including mangroves, wetlands, grasslands, and highlands, contain much of the country's rich biodiversity. The geographical regions all experience different climatic seasons. The dry season, which typically lasts from November to March, is characterised by wind from the Sahara Desert that is dry and dusty, with lower humidity and lower temperatures (World Bank Group, 2021). During the rainy season, which lasts from April to October, there is a lot of rain, especially in the southern and central parts of the country, which promotes lush vegetation and agricultural activity. In general, during August, there is a seasonal transition from long rain campaign to short rain campaign which lasts till October (Ibebuchi and Itohan, 2023).

The country has three distinct climatic zones: a tropical monsoon climate in the south extending over the entire Mangrove region; a tropical guinea savannah climate throughout most of the middle areas – evergreen and a hot, semi-arid Sudan/Sahel climate in the north (Ogunsote *et al*., 2002; World Bank Group, 2021). The depth of the precipitation in Nigeria follows a south-to-north decrease in gradient. Heavy rainfall events are often experienced during the rainy season in the south which could be anytime within the wet season (April to October). After this, the dry season (November to March) arrives with the Sahara wind with dusty harmattan often strong in the north and very brief in the south (Tolulope and Pourvahidi, 2020; World Bank Group, 2021). The annual rainfall in the Mangrove region during the wet season is typically above 2,000 mm and can exceed 4,000 mm in the Niger Delta. However, during the dry season in the Evergreen region, annual average rainfall may be as high as 1200 mm, whereas only 500 to 750 mm of rain or less, falls in the north from June to September. The annual variability of rainfall in northern regions often results in flooding and sometimes droughts towards the north-eastern end (Ekpe, 2014; Ogunsote *et al*., 2002; Tolulope and Pourvahidi, 2020; World Bank Group, 2021; Ibebuchi and Itohan, 2023).

2.2 Datasets

The main datasets used in this study include GNSS observations from the Nigerian GNSS Reference Network (NIGNET), and the ERA5 datasets. The datasets used and their characteristics are shown in Table 1.

Table 1: Datasets acquired for this study

Datasets	Format	Sources	Application	Duration
GNSS: Receiver Observation Data + associated metadata	Observation data in RINEX format together with all associated metadata that aids fast and appropriate post-processing	Nigeria GNSS Permanent Reference Network (NIGNET) CORS data + Script Orbit and Permanent Array Centre (SOPAC)	Applied as input for GNSS processing using GAPS	2011 – 2016
ERA5 Reanalysis	Network Common Data format (NetCDF)	European Centre for Medium-Range Weather Forecasts (ECMWF)	Comparison with GNSS PWV	2011 – 2016

2.2.1 GNSS observations

NIGNET was set up in 2009 by the Office of the Surveyor General of the Federation as a network of sixteen (16) Continuously Operating Reference Stations (CORS) in line with the mandate of the African GNSS Reference Framework (AFREF) (Adebomehin, 2016; Nwilo *et al*., 2016; Ayodele at al., 2019). Seven of these ground–based CORS including ABUZ, BKFP, CLBR, FTY, OSGF, ULAG and UNEC (shown in Figure 1) were selected for this study based on the volume of consistent times series of data available, data logged and latency of data transmission archived for each station (Ayodele *et al*., 2019).

The volume of GNSS data available at each of the seven CORS is presented in Table 2 below.

Table 2: Details of the selected NIGNET CORS

S/N	Station Name	Latitude (°N)	Longitude (°E)	Ellipsoidal Height (m)	Location	% volume of processed data 2011 – 2016
1	ABUZ	11.15	7.65	705.06	Zaria	73.72
2	BKFP	12.47	4.23	250.00	Birni - Kebbi	79.20
3	CLBR	4.95	8.35	57.17	Calabar	66.70
4	FUTY	9.35	12.50	247.40	Yola	81.98
5	OSGF	9.03	7.49	532.64	Abuja	56.89
6	ULAG	6.52	3.40	44.56	Lagos	43.70
7	UNEC	6.42	7.50	254.40	Enugu	73.08

The NIGNET data was downloaded from the NIGNET ftp server and processed using the GNSS Analysis and Positioning Software (GAPS) Precise Point Positioning (PPP) package developed by the University of New Brunswick. GAPS provides users with highly precise point positioning with varied options for exploring both the static and kinematic modes of data capture (Mayaki *et al*., 2019; Urquhart *et al*. 2014).

2.2.2 ERA5 PWV

The ERA5 PWV was downloaded in hourly temporal resolution in Network Common Data Format (NetCDF). The gridded data covering Nigeria was downloaded from the ECMWF database (ECMWF, 2023). Within ArcGIS Pro, the data was extracted at points coinciding with the seven functioning NIGNET CORS and saved in comma-separated value (.csv) format. The spatial resolution of the ERA5 dataset is 0.25° by 0.25° and it covers the period from 2011 to 2016. This ensured that the ERA5 PWV was consistent with the GNSS-derived PWV in terms of the period of coverage.

2.3 Data processing

The NIGNET raw GNSS data was post-processed using GAPS PPP. The accurate satellite clock was applied, along with orbit corrections, and metadata requirements were adequately adhered to. The Scripps Orbit and Permanent Array Centre (SOPAC) performed the data quality checks and cleaning. This process ensures reliable results by mitigating noise, interference, and atmospheric effects, enhancing the accuracy of PPP analysis within the UNB system's advanced capabilities.

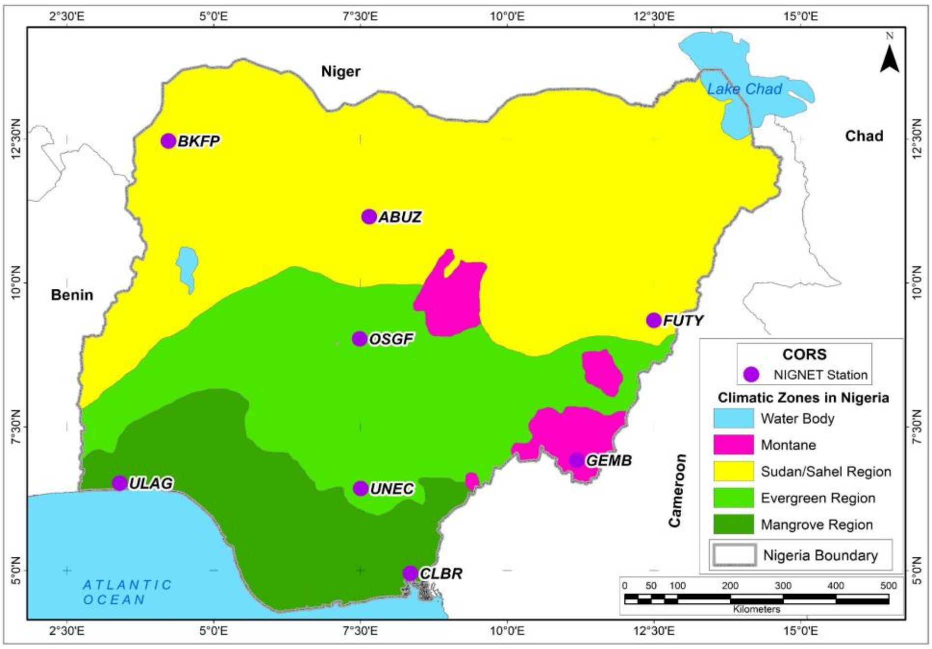

Figure 1: Map showing the seven selected NIGNET stations and climatic zones in Nigeria

The delay along the path of travel, S, of the GNSS signal is called Zenith Tropospheric Delay (ZTD) given by:

$$ZTD = \int_S N(s)\ ds \quad (1)$$

Where, $N(s)$ is the atmospheric refractivity of any radio wave expressed as:

$$N(s) = 10^6(n(s) - 1) \tag{2}$$

and $n(s)$ refers to the refractive indices in the media along the path.

The ZTD is often divided into Zenith Wet Delay (ZWD), which depends on water vapour and temperature and the Zenith Hydrostatic Delay (ZHD), which depends on surface pressure, latitude and height of the receiver station (Bawa *et al.*, 2021). In this study, the GAPS PPP version 6.00 was used as the precise point positioning engine in static mode to estimate ZTD based on parameters preset as shown in Table 3. The a-priori modelling of the tropospheric delay was carried out by a combination of the Niell Mapping Function (NMF) and Saastamoinen model (Mayaki, 2019).

The ZTD obtained was in a 30-second time interval. To derive an hourly dataset from time series ZTD, the mean of ZTD values for every 120 consecutive time points were aggregated using a simple MatLab code. This process provides a consolidated overview of the ZTD on an hourly basis.

The GAPS estimates the station position, receiver clock, zenith wet delay, and an ambiguity per satellite based on epoch, using a sequential weighted least squares filter. The surface meteorological variables used empirically in GAPS to compute the ZHD is the Vienna Mapping Function 1 (VMF1) and the obtained ZHD is then used for the derivation of the ZWD through the PPP estimated ZTD following Equations 3 and 4.

$$ZHD = 0.002277 \times \frac{P}{1-0.00226\times\cos(2\varphi)-0.00000028\times H} \tag{3}$$

Where, P is the surface pressure, H is the ellipsoidal height and φ is the latitude of the CORS

$$ZWD = ZTD - ZHD \tag{4}$$

The PWV was estimated from the GAPS estimated ZWD following Equation 5 as stated by Bevis *et al.* (1992) for GNSS meteorology.

$$PWV = \Pi \times ZWD \tag{5}$$

Isioye *et al* (2017) derived Equation 6 for the conversion factor Π for adoption as a function of surface temperatures, T_s for GNSS meteorological application in Nigeria

$$\Pi = \left(\frac{0.5245T_s+132.12}{0.0053499T_s+1739.07624}\right) \tag{6}$$

Since the units of the ZWD are in millimetres, the PWV was derived for all the stations in millimetres.

Table 3: Options selected for the GAPS PPP post-processing

Items	Selected Option on GAPS
Observation	GPS un-differenced, ionosphere – free linear combination of L1 and L2 carrier phase and pseudo range
Processing Mode	Static
Elevation cut – off	10º
Tropospheric Delay	Vienna Mapping Function 1 (VMF1)
Phase – windup effect	Applied
Ambiguities	Estimated as real numbers
Reference frame	International Terrestrial Reference Frame 2008 (ITRF 2008)
Mapping Function	Vienna Mapping Function (VMF)
Station displacement	Solid Earth tide, ocean tide loading IERS Convention 2010
Satellite Antenna	Phase Centre Offset (PCO) and Phase Centre Variation (PCV) corrected.
Receiver Antenna	PCO and PCV
Orbit and Clock products	IGS final product

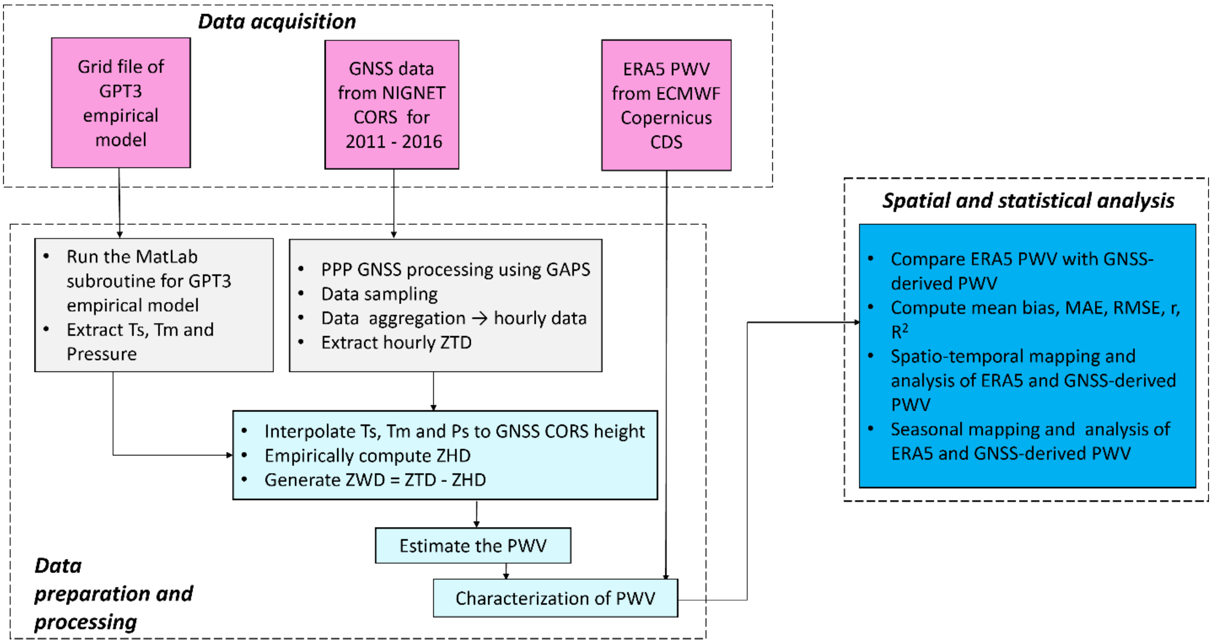

Figure 2: Workflow diagram of the methodology

2.4 *Spatial interpolation of PWV maps*

Maps showing the spatial distribution of PWV were prepared using geographic information system (GIS)-based inverse distance weighted (IDW) interpolation.

IDW is a common deterministic spatial interpolation model with a relatively fast and easy computation and straightforward interpretation (Yu and Wong, 2008; Maleika, 2020; Ohlert *et al.*, 2023). Summarily, IDW estimates the unknown value $\hat{y}$ (S_0) in location S_0, given the observed y values at sampled locations S_i (Yu and Wong, 2008):

$$\hat{y}(S_0) = \sum_{i=1}^{n} \lambda_i y(S_i) \tag{6}$$

The estimated value in S_0 is a linear combination of the weights (λ_i) and observed y values in S_i where λ_i is usually defined as (Yu and Wong, 2008):

$$\lambda_i = \frac{d_{0i}^{-\alpha}}{\sum_i^n d_{0i}^{-\alpha}} \tag{7}$$

In Equation (7), the numerator is the inverse of distance (d_{0i}) between S_0 and S_i with a power α, and the denominator is the sum of all inverse-distance weights for all locations i (Yu and Wong, 2008). The spatial interpolation was implemented using the IDW tool of the 3D Analyst extension within the ArcGIS 10.8.1 software environment. ArcGIS is a software that provides contextual tools and services for mapping and spatial analysis (ESRI, 2023).

2.5 *PWV validation and quantitative analysis*

It is a standard practice to validate reanalysis dataset such as ERA5 PWV by comparison with in-situ observations such as radiosondes or GNSS (Chen *et al*., 2021; Zhang *et al*., 2019; Zhao *et al.*, 2019; Zongwan *et al.*, 2020). Due to the wide availability and proliferation of GNSS data across the globe, it is increasingly being adopted for validating reanalysis datasets such as ERA5 (e.g., Bawa *et al.*, 2022, Nzelibe *et al.*, 2023). In this study, the ERA5 PWVs were validated using estimated PWV from the selected NIGNET CORS over a period of 6 years (2011 - 2016). Additionally, the variation of PWV in the different climatic zones of Nigeria was assessed. To compare the PWV generated from ERA5 and GNSS, the following statistical metrics were adopted in the quantitative analysis: mean, minimum, maximum, mean bias (MB), mean absolute error (MAE), root mean square error (RMSE), correlation coefficient (r) and coefficient of determination (R^2) as shown in Equations 8 - 12.

The coefficient of determination (R^2) is a statistical measurement that examines how differences in one variable can be explained by the difference in a second variable when predicting the outcome of a given event (Scott *et al.*, 2023). It ranges from 0 to 1, where 0 shows no relationship and 1 a perfect fit.

$$MB = \frac{1}{N}\sum_{i=1}^{n}(y_i - \hat{y}_i) \quad (8)$$

$$MAE = \frac{\sum|y_i - \hat{y}_i|}{N} \quad (9)$$

$$RMSE = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{N}} \quad (10)$$

$$r = \frac{N(\sum y_i\hat{y}_i) - (\sum y_i)(\sum \hat{y}_i)}{\sqrt{[N\times(\sum(y_i)^2 - (\sum y_i)^2)]\times[N\times(\sum(\hat{y})^2 - (\sum \hat{y}_i)^2)]}} \quad (11)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \bar{y}_i)}{\sum_{i=1}^{n}(\hat{y}_i - \bar{y}_i)} \quad (12)$$

Where y_i = GNSS PWVs, $\hat{y}_i$ = ERA5 PWVs, $\bar{y}_i$ = mean values of GNSS-derived PWVs for N = number of observations.

3.0 Results and Discussion

3.1 Relationship between ERA5 and GNSS-derived PWV

The global state-of-the-art ERA5 PWV was validated using the GNSS-derived PWV. The time series plots of the ERA5 reanalysis and the GNSS PWV are shown in Figure 3. The ERA5 PWV is closely aligned with the GNSS-derived PWV. Generally, the PWVs are lowest at the beginning and end of the year, and this corresponds with the dry season months (November to March) which have lower precipitation (rainfall). The highest PWVs are generally observed in the wet season months from April to October. There are several perturbations in the PWV values during the dry season months which are likely signatures of the influence and interaction of the tropical continental air mass from the Sahara and maritime tropical air mass from the Atlantic Ocean (e.g., Nicholson, 2013). However, the trend line is generally smoother during the wet season. The gaps in the graph are due to gaps in the data coverage (i.e., seasons where there is no data logged for GNSS observation).

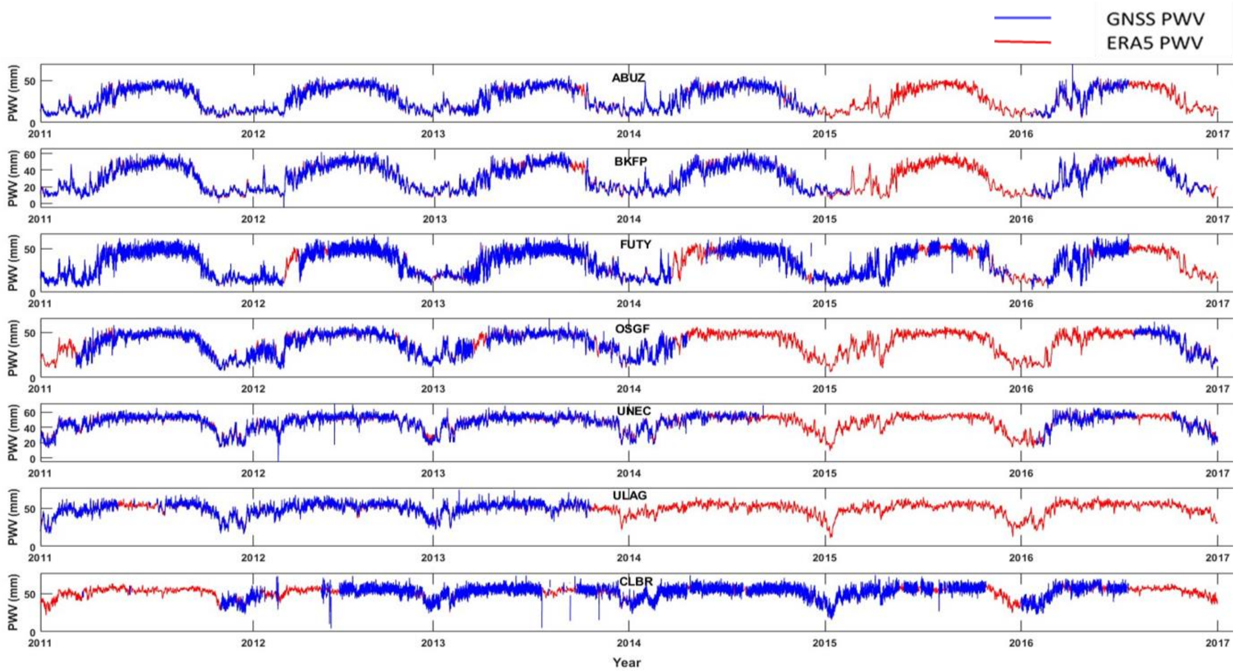

Figure 3: Graphical comparison of ERA5 and GNSS PWVs at the seven NIGNET stations, 2011 – 2016

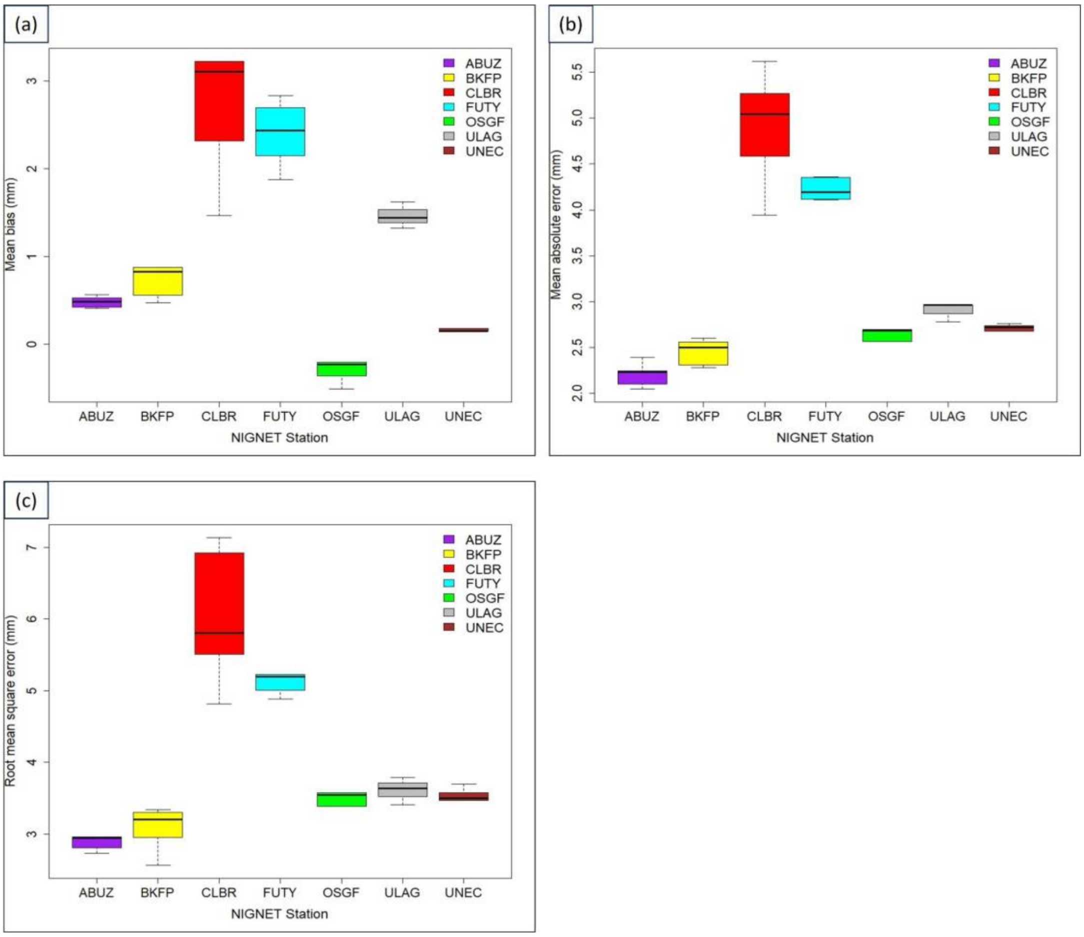

Figure 4: Boxplots of the (a) mean bias (b) mean absolute error, and (c) root mean square error of the ERA5 PWVs, 2011 – 2016

Figures 4a - c present boxplots of the mean bias, mean absolute error, and the root mean square error of the ERA5 PWV for the period 2011 to 2016. Generally, mean bias values from 2011 to 2016 are lowest at OSGF and UNEC respectively (Figure 4a). However, the MAE and RMSE values from 2011 to 2016 are lowest at ABUZ and BKFP (Figure 4b and 4c). CLBR which has the least accurate ERA5 PWV estimates is in the mangrove climatic region. The rainfall pattern in Calabar has been reported to be irregular, with January and September having the lowest and highest number of rainy days respectively (Ogbozige, 2022).

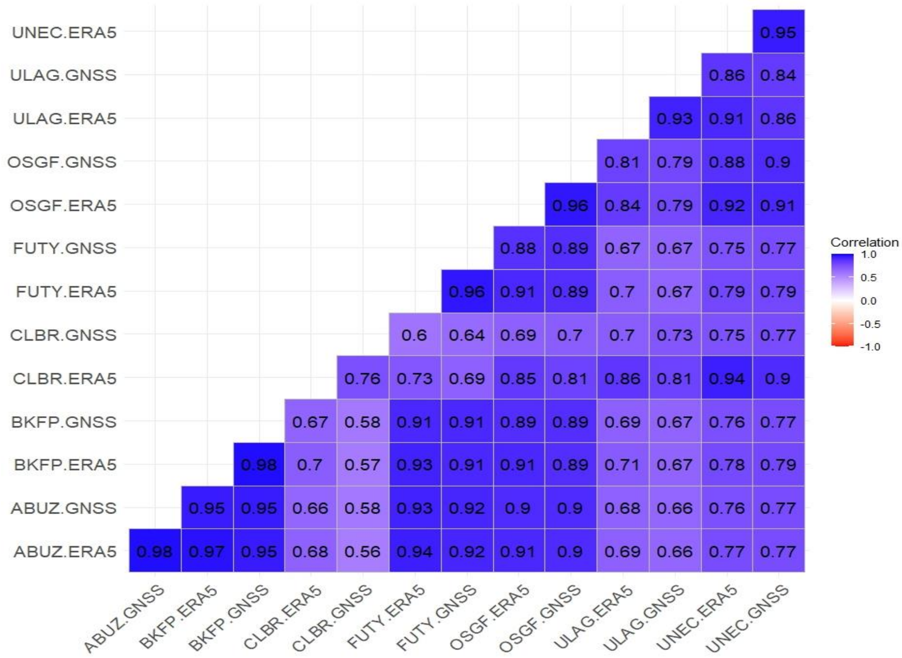

Figure 5: Correlation heatmap of the ERA5 and GNSS PWVs at the seven NIGNET stations, 2011 - 2013

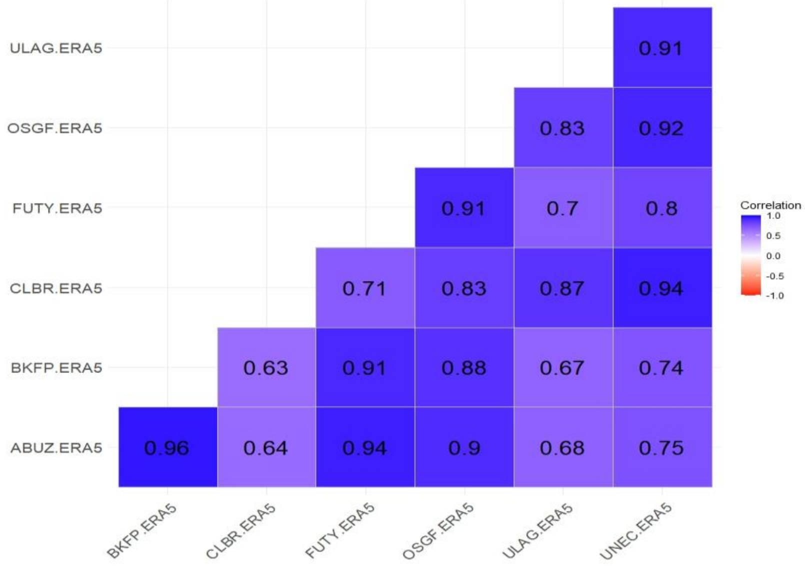

Figure 6: Correlation heatmap of the ERA5 PWVs at the seven NIGNET stations, 2011 – 2016

Figures 5 and 6 present Pearson's correlation heatmaps of the ERA5 and GNSS PWVs at the seven stations for the period, 2011 - 2013. Due to excessive data gaps, the periods from 2014 to 2016 were not included in this initial correlation analysis. The correlations of the ERA 5 and GNSS-derived PWV for all stations are generally above 0.90 except for CLBR with a correlation of approximately 0.8. This may be caused by the anomalous nature of the tropical air mass in this region (e.g., Ekpe, 2014; Ogbozige, 2022).

From Figure 6, it is observed that all the ERA5 PWVs have a very high positive correlation in the Sudan/Sahel region, For example, the correlation between PWV at Zaria (ABUZ) and Kebbi (BKFP) is 0.96; Zaria (ABUZ) and Yola (FUTY) is 0.94; and Kebbi (BKFP) and Yola (FUTY) is 0.91. In the evergreen climatic region, Abuja (OSGF) has a very high positive correlation with Enugu (UNEC), with a correlation coefficient of 0.92. In the mangrove climatic region, the correlation between Lagos (ULAG) and Calabar (CLBR) is very high at 0.87. However, the correlation between Calabar (CLBR) and Enugu (UNEC) is 0.94 which is an indication of the direction of the tropical maritime air mass passing through the direction of the monsoon as it emanated from the southwest following the assertion of Helen (1991).

Regression analysis was carried out between the numerical reanalysis source of PWV and the ground-based GNSS observations at 95% confidence interval and the linear relationship between them at each of the selection stations is given by the following relations.

ABUZ: $GNSS_{PWV} = (0.96165 \pm 0.00372) \times ERA5_{PWV} + (0.98007 \pm 0.00008)$
BKFP: $GNSS_{PWV} = (0.95157 \pm 0.00346) \times ERA5_{PWV} + (1.34570 \pm 0.00010)$
CLBR: $GNSS_{PWV} = (1.01770 \pm 0.00580) \times ERA5_{PWV} + (0.30867 \pm 0.00017)$
FUTY: $GNSS_{PWV} = (1.06180 \pm 0.00590) \times ERA5_{PWV} + (0.62852 \pm 0.00015)$
OSGF: $GNSS_{PWV} = (0.99467 \pm 0.00614) \times ERA5_{PWV} - (0.47593 \pm 0.00022)$
ULAG: $GNSS_{PWV} = (1.07660 \pm 0.00640) \times ERA5_{PWV} - (2.72520 \pm 0.00030)$
UNEC: $GNSS_{PWV} = (1.03870 \pm 0.00730) \times ERA5_{PWV} - (1.93000 \pm 0.00040)$

Table 4 presents the coefficient of determination (R^2) between ERA5 and GNSS-derived PWV at the seven NIGNET stations. There is a good fit between the ERA5 and GNSS-derived PWVs in all the climatic regions where R^2 is above 0.7. Thus, ERA5 PWV can be a good predictor of estimated PWV from GNSS observation especially when long-term monitoring is required, and even when the GNSS station distribution is sparse.

Table 4: Coefficient of determination (R^2) between ERA5 and GNSS-derived PWV at the NIGNET stations

Year	ABUZ	BKFP	CLBR	FUTY	OSGF	ULAG	UNEC
2011	0.96	0.964	0.378	0.903	0.924	0.882	0.92
2012	0.957	0.956	0.476	0.909	0.915	0.8	0.875
2013	0.945	0.949	0.302	0.858	0.886	0.743	0.839
2014	0.945	0.951	0.527	0.721	0.795	-	0.886
2015	-	0.371	0.592	0.889	-	-	-
2016	0.94	0.946	0.736	0.874	0.948	-	0.885

3.2 PWV variation in Nigerian climatic zones

In this section, the PWV variation in the different climatic zones is investigated. The importance of assessing the variability of PWV in different climatic zones lies in its potential to offer insights into regional atmospheric dynamics. Such an understanding can indicate the moisture content of the atmosphere which influences weather patterns and precipitation, and fuel the development of targeted strategies for water resource management and disaster preparedness in specific regions.

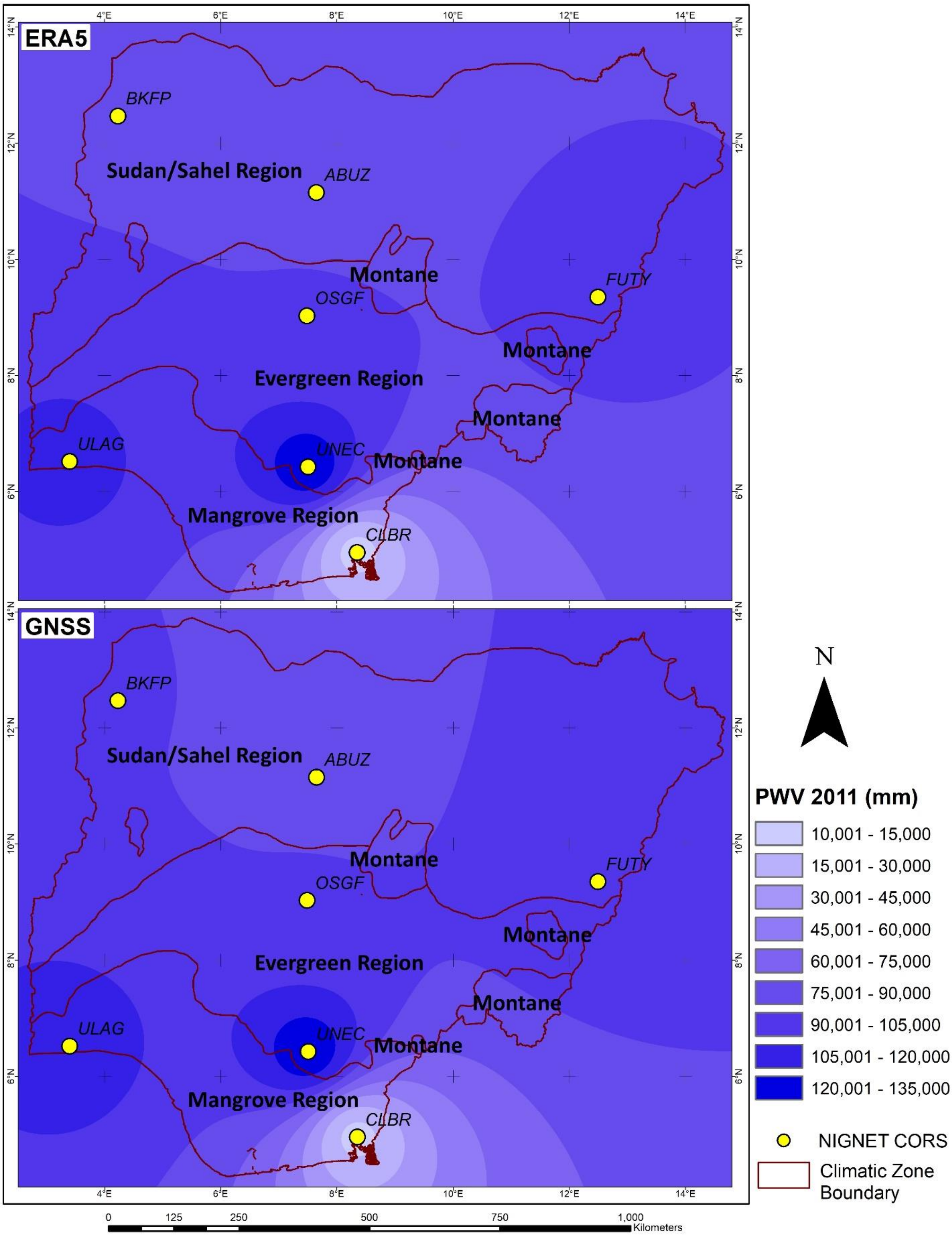

Figure 7: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2011

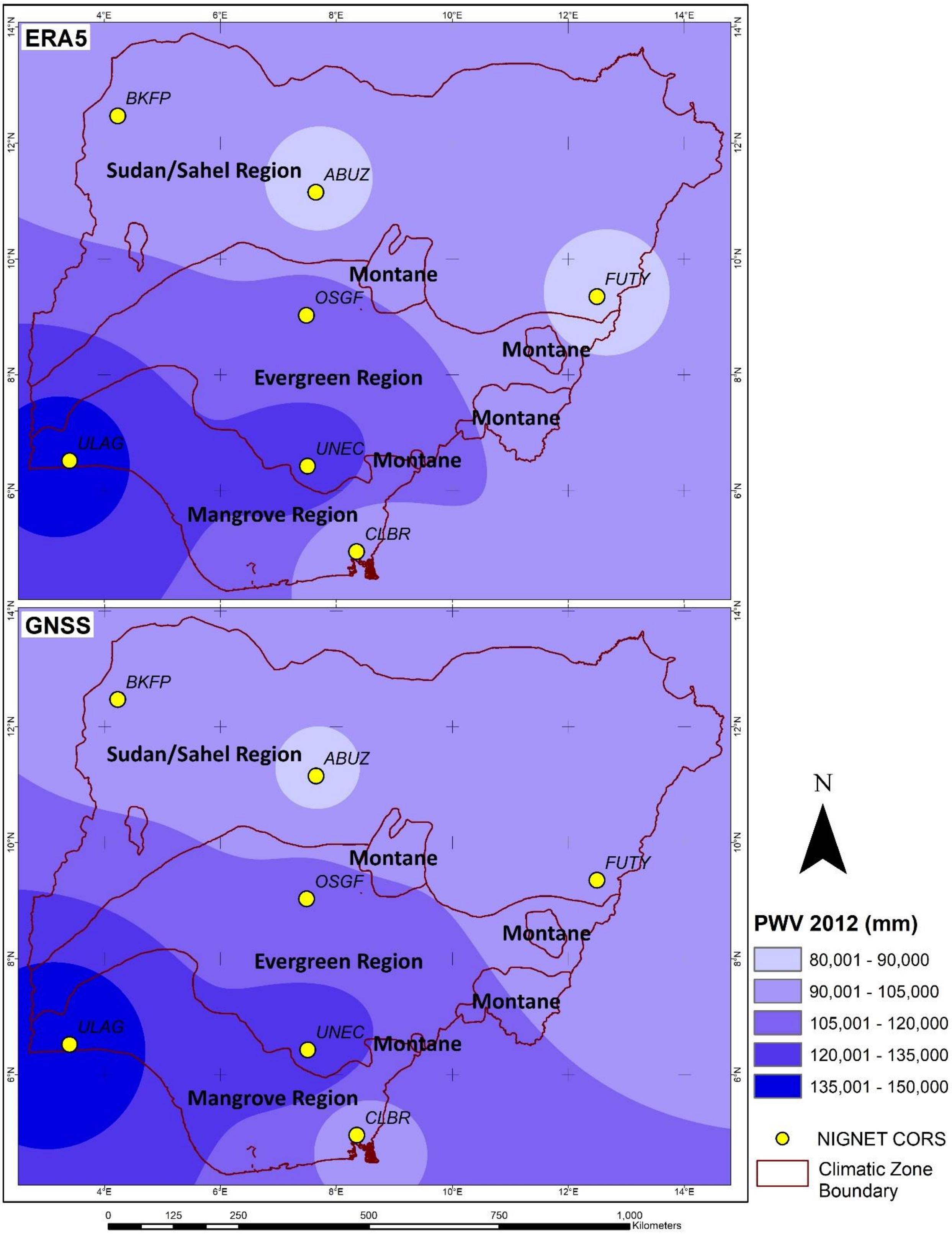

Figure 8: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2012

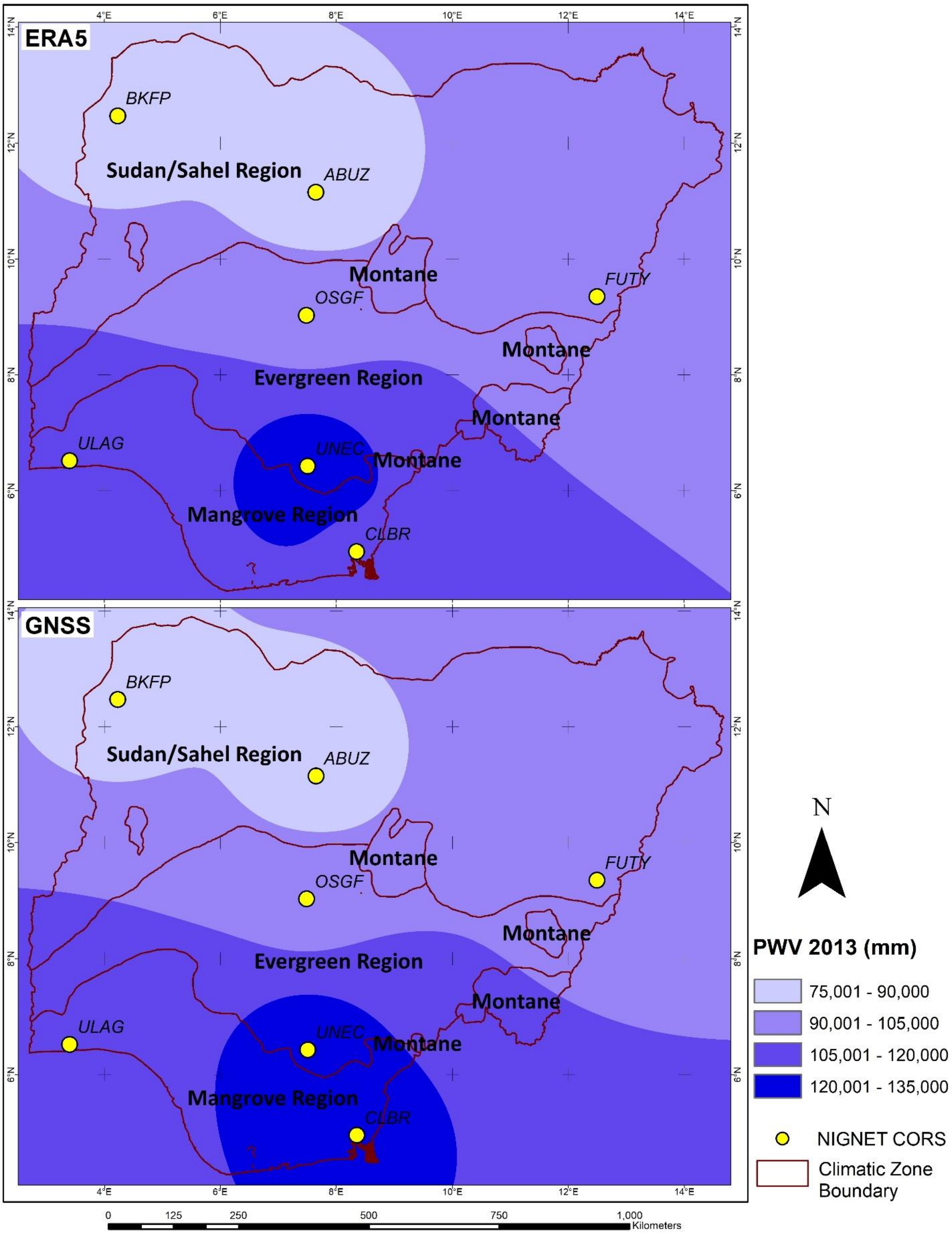

Figure 9: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2013

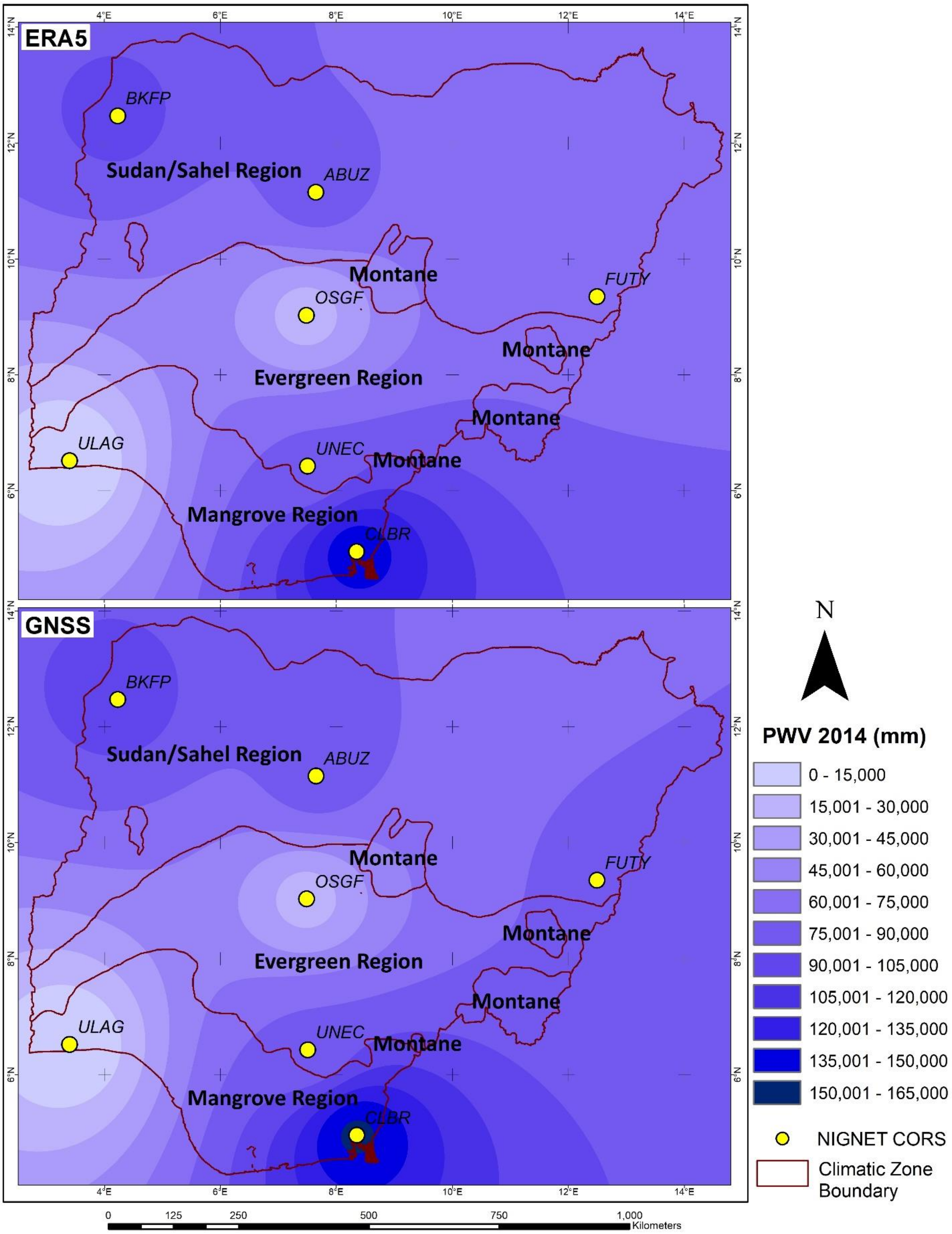

Figure 10: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2014

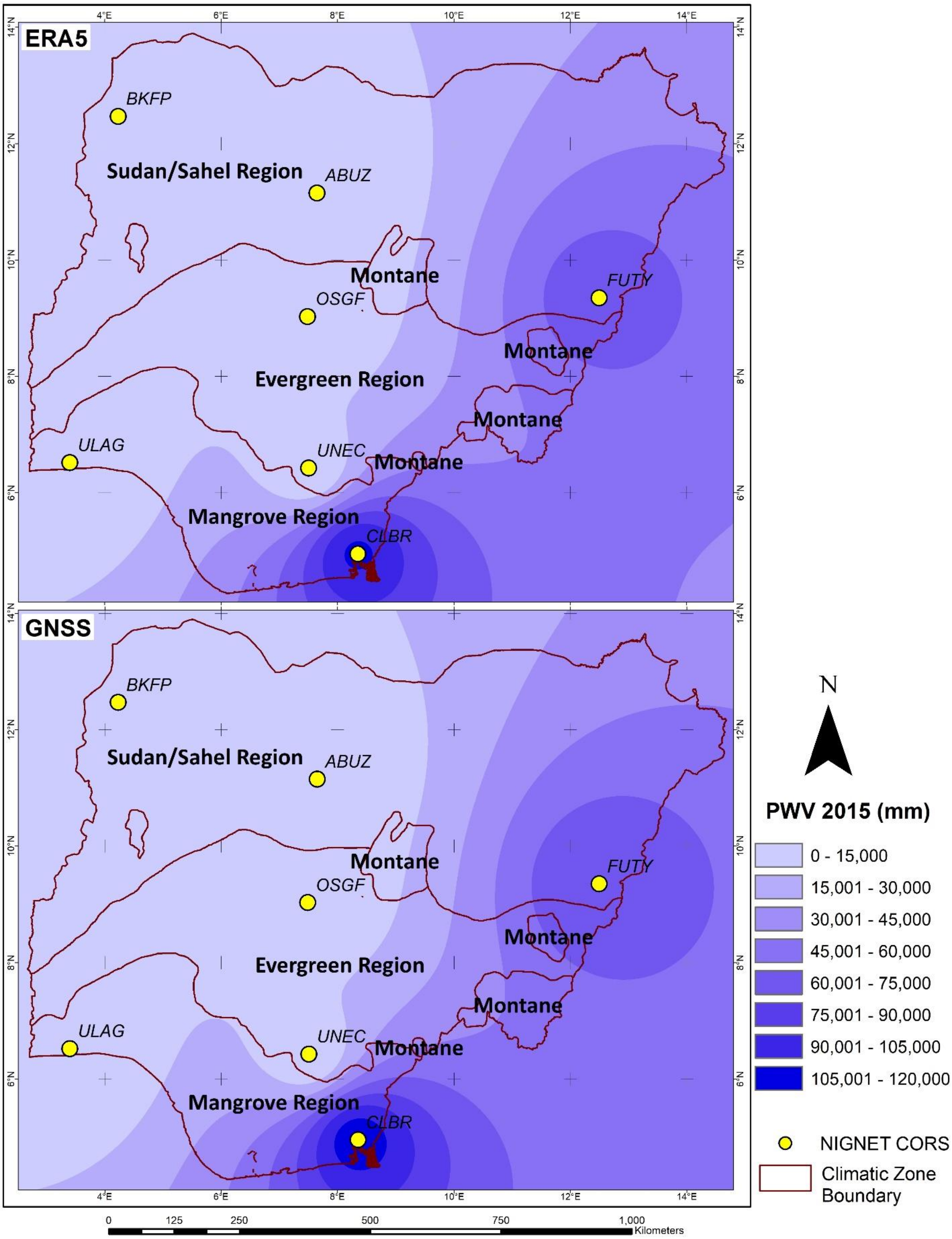

Figure 11: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2015

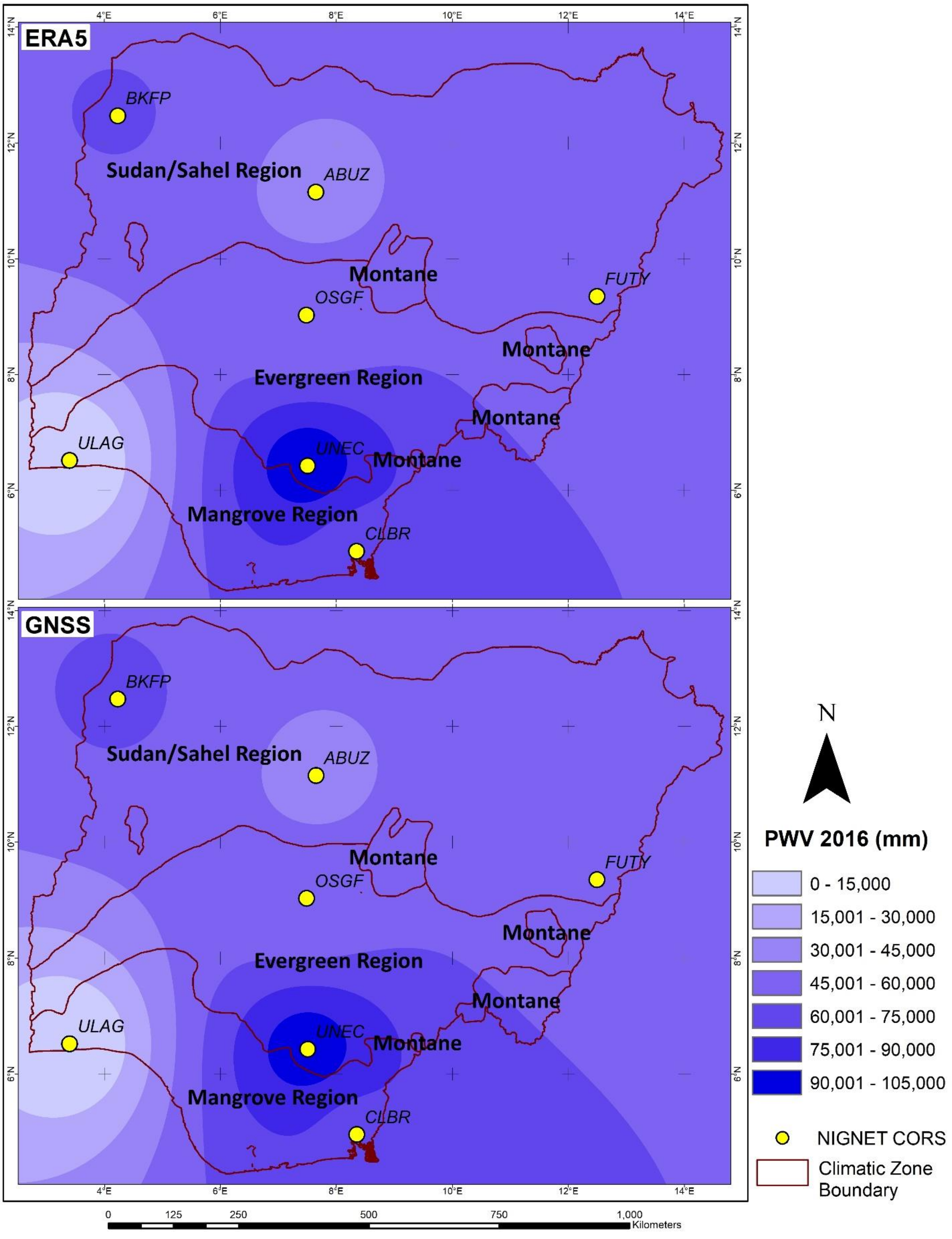

Figure 12: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2016

Figures 7 - 12 present the spatial and temporal variation of ERA5 and GNSS PWV across the Nigerian climatic zones, from 2011 to 2016. In this analysis, the PWVs in the climatic regions are generalised from the PWVs of the respective stations. In the year 2011, the PWV was highest over the station UNEC (Evergreen region) and lowest at CLBR (Mangrove region).

Summarily in 2011 (Figure 7), there was similar spatial distribution between ERA5 and GNSS-derived PWV in the mangrove and evergreen regions, with slight variance in the Sudan/Sahel region. In the year 2012 (Figure 8), the Mangrove climatic region had the highest PWV content over Nigeria, followed by the Evergreen region and the Sudan/Sahel region. There are slight differences in the spatial distribution between ERA5 and GNSS at Yola (FUTY). The high PWV in the mangrove region especially Lagos (ULAG) is possibly a consequence of the disastrous 2012 flooding that occurred in Nigeria. The flooding started in Lagos due to heavy rainfall in July and continued with heavy downpours in the southwestern states (Mangrove region). The flooding that occurred around Adamawa, Taraba, and Benue states sometime around September 2012 was largely due to the opening of Lagdo Reservoir with little contribution of rainfall (NEMA, 2013; Amangabara and Obenade, 2015). The 2012 map shows water vapour content variation in the direction of the flooding experienced in 2012 with a slight variation in water vapour content over Yola (FUTY) where ERA5 was lower than the GNSS estimates

In the year 2013 (Figure 9), ERA5 and GNSS PWV were highly correlated in all the climatic zones with very slight variation in the Monsoon area of the Mangrove region (CLBR) where ERA5 captured less PWV content than the ground-based GNSS. In the years 2014 (Figure 10), 2015 (Figure 11) and 2016 (Figure 12), the spatial pattern of the ERA5 and GNSS-derived PWV maps are similar with significant correlations. Although the ground-based GNSS-derived PWV depicts spatio-temporal variations more accurately, the analysis shows that ERA5 can be utilized as a proxy or alternative dataset to fill in GNSS coverage gaps, or in areas where GNSS data is sparse or non-existent.

3.3 Seasonal variability of PWV in Nigeria

Given the severity of the 2012 rainfall in Nigeria and the associated flooding in 33 states of the federation (Ajaero *et al.*, 2016), this section focuses on the seasonal variability of PWV in the year 2012. Figures 13 and 14 show the seasonal variations of PWV in all the climatic regions of Nigeria during the dry and wet (rainy) seasons of 2012 as captured by the state-of-the-art ERA5 reanalysis and the NIGNET CORS.

In the dry season (Figure 13), the ERA5 PWV ranged from 17, 316.42 – 52, 939.03 mm, while the GNSS-derived PWV ranged from 18, 423.70 to 54, 413.07 mm. There is a considerable similarity in the spatial distributions of the ERA5 and GNSS-derived PWV. The Mangrove region (which is closest to the Atlantic Ocean) recorded the highest PWV. In the northern region where the influence of the continental air mass is the strongest, the PWV is lowest. The map shows a trend in which the PWV decreases at higher latitudes. From Lagos (ULAG), the PWV decreases radially outwards and this is an indication of the direction of the movement of the tropical air mass. Summarily, there is a close consonance in the PWV differentials in both ERA5 and GNSS for the dry season.

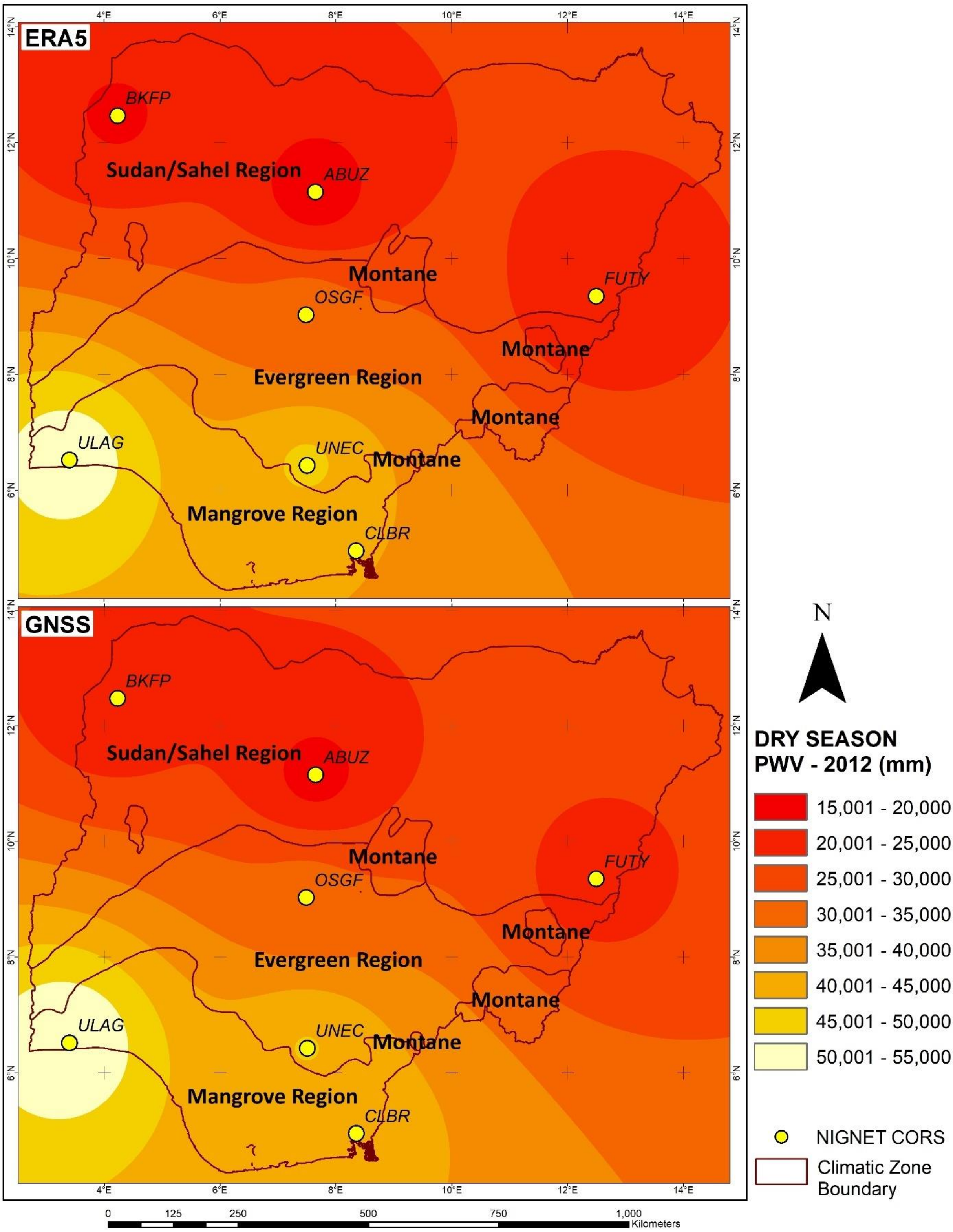

Figure 13: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, dry season 2012

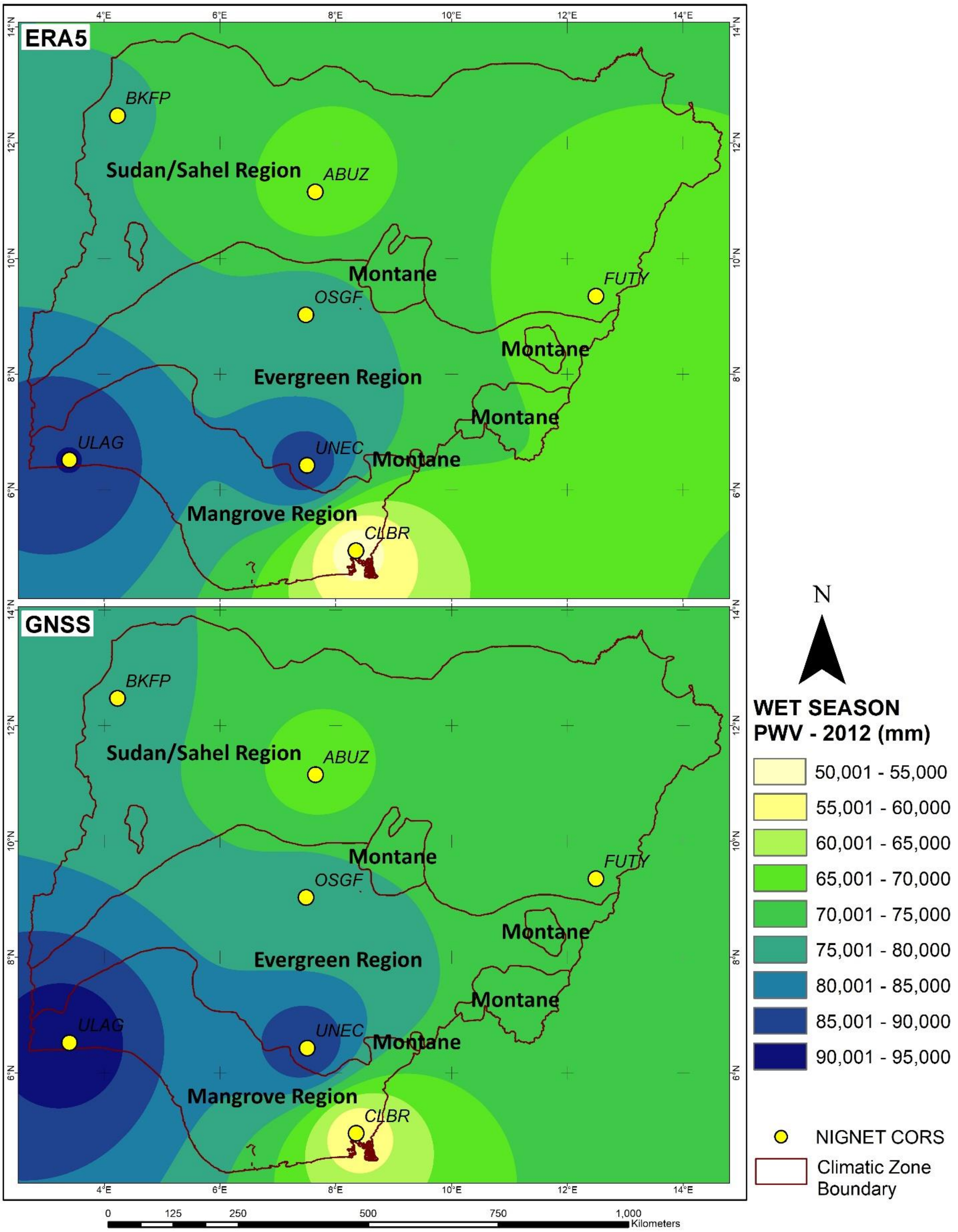

Figure 14: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, wet season 2012

The wet season map (Figure 14) reveals PWV variabilities within and between climatic regions. Within the Mangrove region, the highest PWV was recorded in Lagos (ULAG) while the lowest PWV was recorded at Calabar (CLBR). The same spatial pattern was also observed in the evergreen region at Enugu (UNEC) with a PWV of about 88, 517.24 mm, and other parts of the evergreen region where PWV ranged from 60,000 – 80,000 mm.

The situation is not different in the Sudan/Sahel region where the station at Kebbi (BKFP) recorded the highest PWV in the range of 66, 296.91 – 75, 221.66 mm (Figure 14). Summarily, the ERA5 and GNSS-derived wet season maps have similar spatial patterns. This further validates the importance of ERA5 PWV as a proxy or alternative to in-situ GNSS-derived PWV estimates, especially in areas where GNSS data is sparse or non-existent.

4.0 Conclusion

The global state-of-art ERA5 reanalysis dataset which records the total column of water vapour (i.e., precipitable water vapour) has gained wide popularity among climate researchers. Its peculiar variation in Nigeria's climatic regions has been addressed in this study. The GNSS-derived PWV has been underscored to have a higher spatio-temporal and all-weather accuracy in all the climatic regions of the country. During dry and wet seasons, the PWV is highest at lower latitudes in Nigeria, especially in the mangrove region which adjoins the Atlantic Ocean. The detailed analysis has revealed a high correlation between ERA5 and GNSS-derived PWV at several locations and climatic regions of Nigeria. PWV is a valuable parameter for long-term weather and climate monitoring. More so, PWV acquired from the ERA5 reanalysis can serve as a good substitute to the classic GNSS-derived PWV in understanding historical climatic trends and dynamics.

The need to adequately understand the dynamics of emerging severe weather events is increasing in the face of global climate change. A comprehensive and consistent long-term historical record of climatic parameters that can enhance this understanding and improve emergency preparedness is of utmost importance. The historical database of PWV mapped by ERA5 is viable for long-term studies of PWV over Nigeria for several applications such as hydrological analysis, water resource management, agricultural irrigation and climate change studies. The ERA5 PWV is also valuable for mapping the signature of the West African Monsoon, which is a critical meteorological phenomenon that brings seasonal changes in winds and rainfall to West Africa. The ERA5 PWV also maps the uniqueness of the Intertropical Convergence of the continental and maritime air masses of the Nigerian tropical climate.

Due to the country-wide coverage by ERA5, it is recommended for macro-scale modelling and analysis of PWV over large territories. It can also contribute to the understanding of the dynamics of historical meteorological parameters and peculiar distinctive features of weather and climate. The capability of ERA5 PWV for studying severe weather events has been identified in this study, for example, the case of the 2012 heavy downpour in Nigeria and the associated flooding. Due to the irregular rainfall and PWV variability at Calabar (Monsoon region), a longer time series dataset is recommended for a more comprehensive understanding of the ERA5-GNSS relationship in that region. The observed correlations between PWV and climatic seasons as revealed in this study provide key insights requiring further investigation. The diurnal, monthly and seasonal trend of PWV with rainfall will be investigated in another study.

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