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Precipitable water vapour retrieval and analysis over Nigeria from ground and spaced-based GNSS observations

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ABSTRACT

The recent development of the Global Navigation Satellite Systems (GNSS) radio occultation (RO) technique has overcome many observational limitations inherent in conventional atmospheric sounding instruments and offers an exciting potential for meteorological and climatic researches. This study examines the practicability of GNSS RO technique in observing the atmosphere over Nigeria. A prominent climate change indicator (precipitable water vapour (PWV)) dominant in the upper-tropospheric and lower-stratospheric region were derived from COSMIC profiles (2013-2016) over Nigeria, the results revealed very prominent seasonal patterns in the GNSS RO derived PWV which precisely describes the atmosphere and seasons of the Nigerian region. The PWV agree with ground-based GNSS measurements in the range of -0.40 to 5.58 mm. With the expected improvements and follow on missions for the GNSS RO missions, the quantity and quality of occultation events will improve and lengthen in the Nigerian region thereby making the GNSS RO technique an indispensable tool for future operational atmospheric and climate research in Nigeria and the sub-Sahara Africa region at large.

1. INTRODUCTION

Climate monitoring, prediction and research have become an indispensable pillar of the global effort in climate change mitigation and adaptation. Enhanced correctness about the rapidity of climate change and improved definition of uncertainty levels can inform policy decisions and may accelerate a global consensus on climate change. The need for observation systems with highly accurate estimates of climate variables at global or at least regional coverage is thus paramount to accelerate the global accord on climate change mitigation and adaptation.

Recently, ground and space-based global navigation satellite system (GNSS) atmospheric sounding techniques have evolved as important technologies for observing the troposphere and stratosphere. They both offer excellent capabilities for meteorological and climate change researches (see, Kuleshov et al. 2016). The ground-based technique can automatically monitor the water vapour content in the atmosphere over networks of GNSS stations across the globe (i.e., Jones 2016; Liang et al. 2015; Rozsa et al. 2014). In Nigeria, GNSS observations from ground-based GNSS reference networks have been employed to generate useful atmospheric water vapour information (see, Isioye et al. 2017a and references therein). The GNSS space-based technique or GNSS radio occultation (RO) technique probes the Earth's atmosphere and ionosphere using GNSS receivers onboard Low Earth Orbit (LEO) satellites (see, Anthes et al. 2000; Kursinski et al. 1995). This GNSS technique offers an innovative approach for monitoring global temperatures, pressures, and moisture distributions with a high spatial resolution. The GNSS RO technique provides global coverage, all-weather capability, long-term measurement stability, high vertical resolution and high-accuracy measurements in the middle to upper troposphere, stratosphere and ionosphere. High accuracy of the GNSS RO approach is of specific significance for dependable estimates of the atmospheric peculiarities over regions where conventional upper air sounding observations from radiosondes are sparse or non-existing, i.e., in Africa, the network of radiosonde stations are very sparse and where available are most often than not in a deplorable state (see Isioye et al. 2016).

This paper attempts to appraise the potentials of GNSS RO technique to monitor the weather and climate over Nigeria. To achieve this goal the paper, firstly, gives an overview of GNSS RO missions. Secondly, the paper presents the results of the analysis of atmospheric vapour in the Nigerian region using space-based RO techniques substantiated with in-situ ground-based GNSS measurement. Lastly, the paper gives insight into the planned future expansion of GNSS RO infrastructures. With an expected increase and modernizations in GNSS RO infrastructure, it is expected that GNSS space-based RO techniques would be able to deliver a larger amount of data, which in turn could suggestively advance

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weather forecasting services and climate monitoring, prediction and research in Nigeria or Africa at large.

2. METHOD

2.1. Datasets from Spaced and Ground based GNSS Observations

Post-processed data from the Taiwan/U.S. Formosat-3/COSMIC (Formosa Satellite Mission 3/Constellation Observing System for Meteorology, Ionosphere, and Climate) (Anthes et al. 2008), are used for all discussions in this paper. The post-processed data product from COSMIC is comprised of the raw GPS data, orbit determination, atmospheric profiles, total electron content and ionospheric profiles, scintillations, and tiny ionospheric photometer. We use the level 2 product "wetPrf". The "wetPrf" atmospheric profiles offer water vapour pressure, temperature, refractivity and water vapour information with a vertical resolution of 0.1 km and altitude range of 0 to 39.9 km.

Ground based GNSS derived precipitable water vapour (PWV) estimates were used to evaluate the COSMIC derived PWV. Ground-based GNSS meteorology has long offered the prospect of complementing other meteorological observations by providing an integrated vertical column of PWV content over respective GNSS sites. Dataset from the from the new Nigerian GNSS network (NIGNET) in Nigeria were utilized in this study (Jatau et al. 2010; Naibbi and Ibrahim 2014). These stations are primarily for surveying and positioning applications in Nigeria.

To investigate seasonal variations in the PWV, the estimated PWVs were grouped into four seasonal groups that typically represents the seasons in Nigeria, i.e., December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON).

2.2. PWV Retrieval from Spaced based GNSS Observations

To analyse the state of atmospheric water content from GNSS RO in the Nigerian region, we used GNSS RO data from COSMIC for the period of 2013-2016. We adopted an innovative approach to the estimation of PWV from GNSS RO profile data, first the zenith tropospheric delay (ZTD) was estimated from the numerical integration of a profile refractivity using the following relations;

$$ZTD = \int_{l}^{r} (n-1)ds = 10^{6} \int_{l}^{r} N ds \qquad (1)$$

In the discrete form, the equation (1) can be written as;

$$ZTD \approx \sum_{p}^{r} \left(\frac{N_{i+1} + N_{i}}{2} \right) \cdot \Delta s_{i} \qquad (2)$$

In equation (2), Δs_i is absolute difference between successive heights of an individual occultation profile, N_i and N_{i+1} are successive refractivity values at respective heights, i is the index denoting discrete heights/refractivity pairs and k is the number of discrete linear segments between the occultation satellite (r) and the lowest (or ground) point of the occulting event. A total of 1902 daily occultation profiles were processed for the period of 2013 to 2016 for the Nigerian region. The resulting ZTD was grouped into seasonal averages.

In furtherance of discussions to explore the potential of the occultation technique in estimating atmospheric water content over Nigeria, we estimated the Precipitable water vapour (PWV) from the ZTD values for each of the 1902 wet profiles from COSMIC observations. To achieve this, we choose an approach to separate the ZTD into the dry (ZHD) and wet (ZWD) components. The ZHD was estimated using the relation of Saastamoinen (1972) as presented in equation (3),

$$ZHD = 0.002277 \times \left[\frac{P}{1 - 0.00266\cos(2\phi) - 0.28 \times 10^{-6} \times h} \right] \qquad (3)$$

where the pressure (P) in mbar is the pressure at the ground point of the occultation profile, the ground latitude ϕ of the occultation event is in radians and the height (h) is the corresponding height of the occultation event at ground point (in m). The resultant ZHD was subtracted from the ZTD to get the ZWD, we then adopted the formula of Isioye et al. (2017a) as presented in equation (4) to estimate the PWV for each occulting event. Equation (4) is suggested to users as a handy formula to estimate PWV (in mm) in Nigeria using $T_s\,(K)$ and ZWD (mm) as inputs. Again, PWV estimates were grouped into seasonal means.

$$PWV = ZWD \times \left[9.80392 - \frac{16917.64}{0.053499 T_{s} + 1739.07624} \right]. \qquad (4)$$

2.3. PWV Retrieval from Ground-based GNSS Observations

Daily GNSS observation data files in RINEX format with a 30-seconds sampling rate were collected from seven stations representing the different climatic zones in Nigeria for the period 2013-2016 via file transfer protocol (ftp) from the NIGNET server (http://server.nignet.net/). The GNSS stations were carefully selected based on their proximity to automatic (synoptic) weather observing stations (AWOS). Data from the AWOS were obtained from the Nigerian Meteorological Agency (NIMET). The GAMIT/GLOBK software (Herring et al. 2006) was used to estimate the ZTD. It employs a forced batch least squares inversion process. The GAMIT/GLOBK software parameterises the ZTD as a stochastic deviation of the uncomplicated representation of the Saastamoinen hydrostatic delay model (see Saastamoinen 1972) with a Gauss–Markov power density of $2cm / hour^{1/2}$.

The ZTD at each GNSS station was estimated daily within a 24-hour window session. The International GNSS Service (IGS) final orbits (SP3) and IGS final Earth rotation parameter (ERP) products were used. Satellite elevation cut-off was set to 10° during the data processing. Station coordinates were heavily constrained to their ITRF 2008 values (Altamimi et al. 2011). Solid earth tide based on the IERS03 and FES2004 models were used for solid earth tide and ocean tide loading corrections, respectively. The constraint used for zenith delay was 0.2m, as it is recommended to set it loosely enough to encompass any error in wet delay (Herring et al. 2006). Satellite antenna phase centre offset and phase centre variation is based on AZEL for IGS absolute ANTEX files (Gendt and Schmid, 2005). The a priori tropospheric model used is the Saastamoinen model (1972) based on meteorological sources from the Global Pressure and Temperature (GPT) model. The Vienna Mapping Function (Boehm et al. 2006) was used to calculate the zenith delay. To retrieve PWV estimates from GNSS-derived ZTDs, station temperature and pressure values are fundamental to separate the ZTD into its wet and dry components. Thus, surface temperature and pressure data from nearby AWOS were transferred to the GNSS sites employing the technique demonstrated by Musa et al. (2011). The resultant ZWD component was transformed to PWV using the formulation of Isioye et al. (2017b) presented herein as Equation (4):

3. RESULTS AND DISCUSSİON

The ZTD estimates as presented in the Figure 1 show clear evidence of seasonal variations which are in good agreement with the result of Isioye et al. (2017b) from ground-based GNSS stations across Nigeria. Nigeria's climate is characterized by strong a latitudinal dependence and becomes increasingly drier as one moves northwards from the coast of the Atlantic Ocean. Rainfall is the main climate indicator and there is a discernible difference between the wet and dry seasons across Nigeria. By April or May of every year, the rainy season is underway in most parts of the south of the Niger and river Benue valleys. Farther north the rains do not begin until the months of June or July. From the months of December through February northeast trade winds, called the Harmattan, sweeps through the country. In addition, these winds are often loaded with dust particles from the Sahara Desert giving rise to characteristic Harmattan haze which reduces visibility.

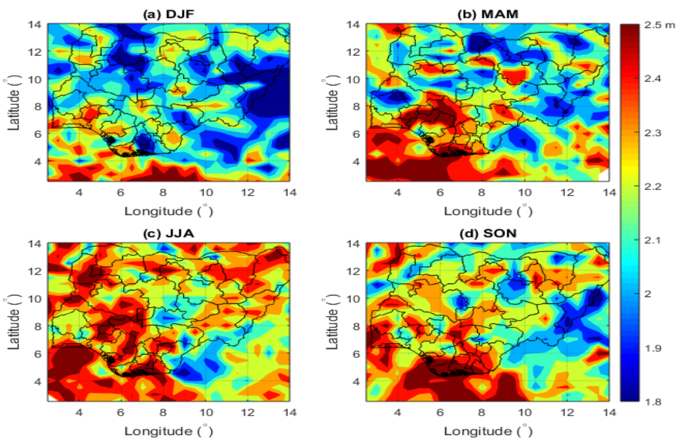

Figure 1. *Seasonal mean ZTD, a) DJF, b) MAM, c) JJA, c) SON derived from COSMIC for the period of 2013-2016 over the Nigerian region*

The Figure 2 shows the PWV from COSMIC observations for the four the different seasons. Expectedly, it can be seen that the PWV also follow similar pattern with the ZTD. The maximum or very high amount of PWV was recorded in the moths of June, July and August which often symbolises the peak of the wet season in Nigeria.

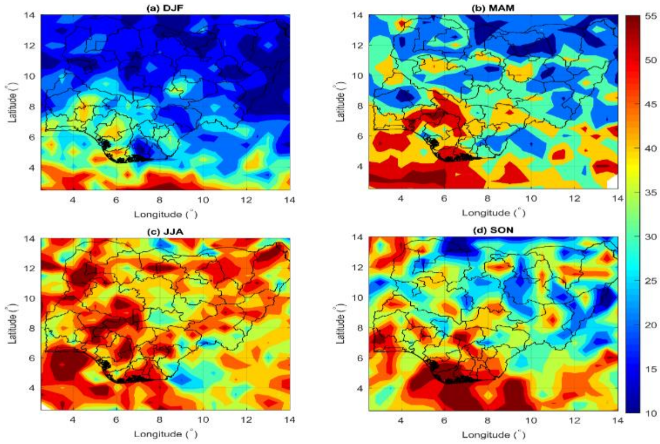

Figure 2. Seasonal mean PWV, a) DJF, b) MAM, c) JJA, c) SON derived from COSMIC for the period of 2013-2016 over the Nigerian region

Figure 3 presents the PWV values for the four seasons. According to Figure 3, the seasonal PWV confirms an apparent agreement with those in figure 2 for the GNSS RO. Both Figures 2 and 3 exhibits lower values in the dry season (DJF and MAM) and higher values in the wet season (JJA, SON), which reflects that in the wet (rainy) season, because of the strong moisture field (high water vapour pressure) the PWV magnitude is higher. PWV values at all the GNSS stations and GNSS RO events exhibit a recognised seasonal signal, which can be explained by a cosine function, as the increase to the maximum in the JJA season, which is the peak of the rainy season in both the north and south of Nigeria, and a decrease to the minimum in the months of DJF, the dry season in the south and the Harmattan in the north of Nigeria. There is little rain in the months of MAM and SON in the north and the temperature is high, while the south is not as dry as the north, thus the climate in the south is very humid and tends to keep the PWV values very high.

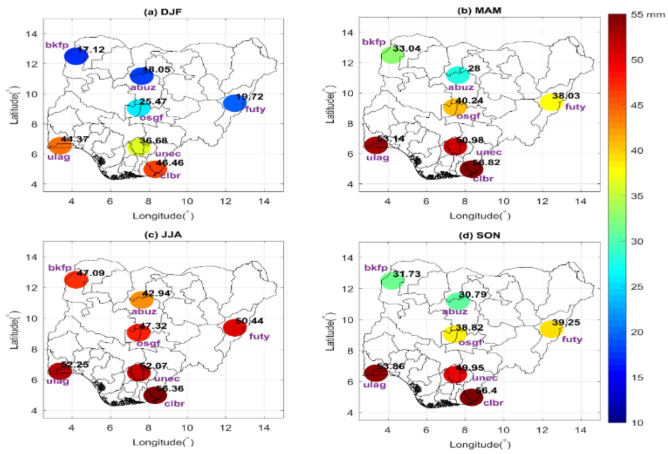

Figure 3. Seasonal mean PWV, a) DJF, b) MAM, c) JJA, c) SON derived from NIGNET for the period of 2013-2016 over the Nigerian region

From the Figures 2 and 3, the amount of PWV is greatly varied at the coastal regions of Nigeria. For instance, the magnitude of PWV is greater at all seasons along the shorefront of the Atlantic Ocean at the ground GNSS stations (CLBR and ULAG) and the occultation points. The seasonal range (i.e. difference between maximum and minimum seasonal values) of PWV at the different GNSS stations as seen in Figure 3 is 24.88 mm, 10.36 mm, 30.72 mm, 9.49 mm, 15.39 mm, 21.85 mm and 29.97 mm for ABUZ, CLBR, FUTY, ULAG, UNEC, OSGF, and BKFP, respectively. It is obvious that the range in PWV at the stations increases with latitude (i.e., movement from south to north), this pattern is also evident in PWV from GNSS RO observations. A sharp increase in the range values is seen at the location of GNSS stations (ABUZ, FUTY, OSGF, and BKFP) and occultation points in the northern part of Nigeria. This is expected because of the extreme cold and hot weather during the dry season in the northern part of Nigeria, which often results in great variations in surface temperature. These results show that variability in PWV estimates as observed by both GNSS techniques is closely related to rainfall and confirms the efficiency of the GNSS techniques in storm prediction and possibly in improving future forecasting models in Nigeria.

To further, ascertain, the agreement between ground-based GNSS derived PWV and that from GNSS RO, we found and calculated the mean absolute difference between the duo techniques for occultation events at a maximum distance of 100km from the individual GNSS station. The summary of the result is presented in Table 1 for the four seasons, in some of the seasons; there were no occultation events within the 100km buffer zone from the GNSS station(s).

Table 1. Mean absolute difference of precipitable water vapour (PWV) estimates from GNSS RO and ground-based GNSS over Nigeria

Ground GNSS Station	Mean Difference (COSMIC – Ground GNSS Station) (mm)			
	DJF	MAM	JJA	SON
abuz	1.323	4.425	4.655	-
bkfp	2.235	0.400	5.576	2.459
clbr	-	3.94	0.577	0.580
futy	2.283	0.895	2.668	1.245
osgf	0.800	2.355	1.052	-
unec	6.47	0.995	0.623	0.403
ulag	4.973	1.687	0.700	2.425

From the Table 1, it is evident that the GNSS RO can estimate PWV to accuracy limit of less than about 5mm as compared to the ground-based GNSS technique. These results are very attractive for weather forecast, climate and atmospheric research since PWV is a very important climate pointer.

4. CONCLUSION

The paper has demonstrated the capability of the GNSS RO technique for the monitoring the Nigerian weather and climate. This emerging technique uses radio signals between the Low Earth Orbit (LEO) and GNSS satellites, probes the Earth's atmosphere and ionosphere from space. The quality of GNSS RO derived atmospheric profiles was assessed with other observing systems in this study, the outcome shows good agreement with the Ground-based GNSS stations and have been considered as a good data source for atmospheric and climate related researches. The GNSS RO technique has a strong potential to provide useful information for assimilation as a new data source into the Nigerian weather forecasting framework. The recent improvements in the COSMIC (COSMIC-2), GRACE (GRACE-FO), and proposed improvement in MetOp missions (MetOp-SG) are expected to increase the number of RO events globally and will further enhance the capacity of the technique. Such a large volume of stream-in new high resolution atmospheric profiles will no doubt have great impacts on future meteorological studies and applications.

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