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Evaluation of GNSS Radio Occultation Technology for Meteorological and Climate Applications over Nigeria

Moses M.[1,*], Ibrahim U.S.[1], and Akomolafe E.A.[1]
[1]Department of Geomatics, Ahmadu Bello University, Zaria, Nigeria
*Corresponding Author: mosesmefe@gmail.com

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ABSTRACT

The lack of conventional ground-based observations in the sub-Saharan African region poses significant challenges to understanding and monitoring the atmosphere. This is particularly true in the upper-tropospheric and lower-stratospheric (UTLS) regions, where the atmosphere's dynamic nature and complex processes make observation difficult. However, the development of the GNSS radio occultation (RO) technique presents an exciting opportunity for meteorological and climatic research. This study focuses on assessing the feasibility of using the GNSS RO technique to observe the atmosphere in Nigeria. It evaluates the different GNSS RO missions and examines the distribution of events across Nigeria. The study found that the coverage of radio occultation (RO) missions varies significantly, depending on the orbit design of GNSS and low-earth orbiting satellites. Additionally, the quality of atmospheric profiles, specifically from the COSMIC mission, was assessed by comparing them to radiosonde observations in Nigeria. The results demonstrated strong agreement between the COSMIC profiles and radiosonde data, with absolute mean errors of 1.42C, 0.97mbar, 0.34mm/km, and 0.58mbar for temperature, pressure, refractivity, and vapour pressure profiles respectively. Lastly, two prominent climate change indicators (tropopause height (TH) and precipitable water vapour (PWV)) dominant in the UTLS region were derived from COSMIC profiles (2013-2016) over Nigeria, the results revealed very prominent seasonal patterns in the GNSS RO derived TH and PWV which precisely describes the atmosphere and seasons of the Nigerian region. The TH and PWV agree with radiosondes and ground-based GNSS measurements in the range of -1.98 to 3.13km and -0.40 to 5.58 mm, respectively. Improvements and future missions in GNSS RO will enhance the quantity and quality of occultation events in Nigeria. As a result, the GNSS RO technique will become an indispensable tool for operational atmospheric and climate research in Nigeria and the broader sub-Saharan Africa region
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Keywords: Global Navigation Satellite System (GNSS), Radio Occultation (RO), Tropopause height, Zenith Tropospheric Delay, Climate change, Precipitable Water vapour, Meteorology

1.0. 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 (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 (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 (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 (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 is very sparse and where available are most often than not in a deplorable state (Isioye et al., 2016).

Over the past two decades, various government agencies around the world have been launching different GNSS RO missions and projects to probe stratosphere and troposphere. Currently, GNSS RO data is used as an additional data source by weather centres at Germany, United States, France, Canada, Japan, Taiwan, and the European Centre for Medium Weather Forecasting (ECMWF). The ECMWF and many meteorological institutes all over the world have successfully assimilated GNSS RO data into numerical weather prediction (NWP) models. The situation in Africa appears quite different; there are no records of GNSS RO products being assimilated into local NWP or mesoscale models by meteorological offices/agencies in the region. Importantly, the GNSS RO products must be evaluated at different scales over the African region to prove its potential in weather monitoring and climate studies in the region.

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 appraises the promises of the GNSS RO technique for meteorological and climatological applications over Nigeria in three parts. Firstly, the paper reviews the status of the various GNSS RO missions and analyses the distribution of GNSS RO events from varying RO missions over Nigeria. Secondly, the paper presents the results of the analysis of atmospheric characteristics (temperature and moisture) in the African region using space-based RO techniques substantiated with in-situ radiosonde and 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 weather forecasting services and climate monitoring, prediction and research in Nigeria or Africa at large.

1. 1 Concept of GNSS Radio Occultation and Missions

The geometry for RO soundings is shown in Figure 1. As the two satellites move, the ray – shown in red – 'probes' through the atmosphere either downwards (a 'setting' occultation) or upwards (a 'rising' occultation). The ray is refracted ('bent') by density gradients in the atmosphere. By equating the phase (or Doppler) of the received radio signal with that expected from the *in vacuo* straight line path between the satellites, the total integrated bending angle can be calculated. From the 'profile' of bending angle (α) as a function of impact parameter (a), a profile of refractivity (N) as a function of geometric height can be obtained .The refractivity is expressed as (Bevis et al., 1994);

$$N = 77.6\frac{P}{T} + 3.73\times10^5\frac{e}{T^2} + 1.4W - 4.03\times10^7\frac{N_e}{f^2} \tag{1}$$

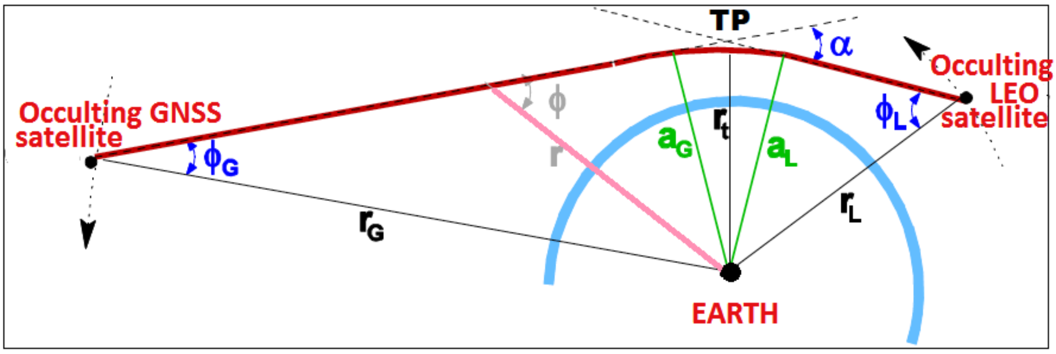


Figure 1: Geometric Representation of the GNSS Radio Occultation Concept

In equation (1), P is atmospheric pressure (in mbar), T is the temperature in Kelvin, e is the partial pressure of water vapour (in mbar), N_e is the electron density (in electron m^{-3}), f is the transmitter frequency in Hertz, and W is the mass of condensed water in the atmosphere(in gm^{-3}). The first two terms of Equation (1) represent the dry and wet contribution of the neutral atmosphere. The effects of the other two terms are often neglected in the process of retrieving profiles of pressure, temperature and humidity with geopotential height from the equation (1) and the hydrostatic equation. Hence, the direct atmospheric products of the GNSS RO retrievals are the electron density profiles in ionosphere, the temperature and pressure profiles in the upper troposphere and lower stratosphere (UTLS) regions, and the water vapour profiles in the middle and low levels of the troposphere (Fu et al., 2007). A schematic view of the GNSS RO retrieval process is shown in Figure 2, however, it is noteworthy that details of these steps are out of the scope of this paper. The detailed explanation of the concept of the RO technique and the process for the derivation of atmospheric parameter and geophysical quantities is well documented (Kursinski et al., 1997).

The first experimental GNSS RO mission, called GPS/MET (i.e. GPS Meteorological experiment) was launched by UCAR (University Corporation for Atmospheric Research, U.S.) in 1996 and was a breakthrough success for the GNSS-RO technique, accurate atmospheric profiles were successfully retrieved from it and decommissioned in two years after (Ware et al., 1996).

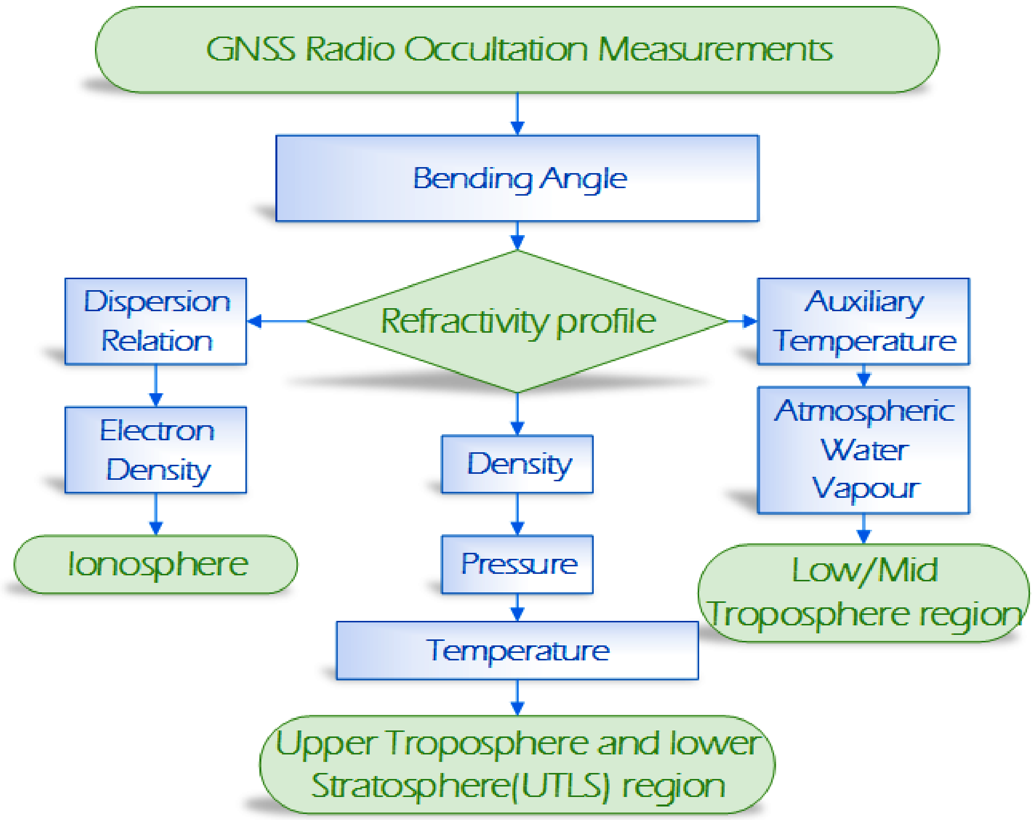


Figure 2: Schematic diagram of the GNSS Radio Occultation retrieval process

After the first RO experiment in 1996, many countries, such as USA, Germany, Austria, Russia, Finland, Italy, Denmark, Argentina, Brazil, South Africa and Korea have flown numerous RO missions to probe the troposphere and stratosphere. A number of this missions failed at inception or after few runs. Very notable in the category of failed missions are SUNSAT, Ørsted, and SAC-C missions. SUNSAT and Ørsted missions both launched in 1999 by South Africa and Denmark operated over a few years (Larsen et al., 2005; Mostert and Koekemoer, 1997). The SAC-C was an international effort by the USA, French, Brazil, Denmark and Italy, and was launched in 2000, and produced data for four years (Hajj et al., 2002).

Follow on satellite missions such as CHAMP (CHAllenging Mini-satellite Payload) also generated high quality and stable information of the atmosphere and ionosphere (Wickert et al., 2004). CHAMP (Germany) has a history of quality RO data from 2001 to 2008. Such a long period of continuous RO data permitted high quality climatological studies. In 2002, NASA launched an innovative set of twin LEO satellites GRACE (Gravity Recovery and Climate Experiment), it was designed for measuring gravity recovery and atmospheric observations and mission life of five years but has since continued to provide observations (Beyerle et al., 2005).

On-going RO missions include the Taiwan/U.S. Formosat- 3/COSMIC (Formosa Satellite Mission 3/Constellation Observing System for Meteorology, Ionosphere, and Climate) (Anthes et al., 2008), which was launched in 2006. The European MetOp/GRAS mission (Loiselet et al., 2000) started in 2006. It consists of a series of three satellites launched in sequence to operationally provide RO data until at least the year 2020 (Luntama et al., 2008). The German TerraSAR-X and Trandem-X satellites launched in 2007 and 2010 respectively, provide atmospheric RO data (Wickert et al., 2009). Since recently, also the Spanish ROHP-PAZ launched in 2013 is a proof-of-concept experiment: for the first time ever, GNSS RO measurements are to be taken at two polarizations, to exploit the potential capabilities of polarimetric radio occultation for detecting and quantifying heavy precipitation events (Cardellach et al., 2015). Table 1 is a piece of summary information on some operational GNSS RO missions across the globe. The increase in the number of GNSS RO mission since 2006 after the coming of COSMIC has been very enormous, it therefore pertinent to analyse the spatial and temporal distribution of the events from the different RO missions since they vary in the different regions of the world.

Table 1: Brief Description of some Operational GNSS Radio Occultation Missions

No.	Mission	Country	Altitude	Inclination	Operational Status
1	FORMOSAT-3/COSMIC	USA/Taiwan	800	72	2006 - present
2	FY-3C	China	836.4	98.75	2013 - present
3	GRACE-1	Germany	485	89	2002 - present
4	KOMPSAT-5	Korea	550	97.6	2013 - present
5	MEGHA - TROPIQUES	India / France	865.6	20	2011 - present
6	MetOp	ESA	817	98.7	2007 - present
7	OceanSat-2	India	720	98.2	2009 - present
8	SAC-D	Argentina	657	98	2011 - present
9	TerraSAR-X	Germany	514.8	97.5	2007 - present
10	TANDEM-X	Germany	514.8	97.5	2010 - present
11	ROHP- PAZ	Spain	514	97.4	2018 - present

The current study focuses the discussion on missions which are operational at the moment and with plans to follow up missions. To this end, the coverage and distribution of RO events from Formosat- 3/COSMIC, GRACE-1, MetOp –A &B, and TerrraSAR-X RO missions over the Nigerian territory is discussed in the next section of the paper. More attention will be accorded to the COSMIC mission with regard to expectations from the mission in its planned follow up mission, which appears more promising than other missions. Additionally, COSMIC is a highly efficient RO mission that has met wide scientific applications in operational weather forecasts (Anthes, 2011) and global atmospheric studies (Schmidt et al., 2010).

2.0 Methodology

This section describes the methodology used to assess the practicability of the GNSS Radio Occultation (RO) technique in observing the atmosphere over Nigeria. It includes an appraisal of GNSS RO missions and their coverage, validation of atmospheric profiles from the COSMIC mission, and derivation of climate change indicators. The section highlights the agreement between COSMIC and radiosonde observations, and the potential of GNSS RO for future atmospheric and climate research in Nigeria.

2.1 Data Collection

The study collected GNSS Radio Occultation (RO) data from various missions, including the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission. The data covered the period from 2013 to 2016 over Nigeria. This dataset provided valuable information about the atmosphere in the region and formed the basis for the subsequent analysis and evaluation of the GNSS RO technique. Radiosonde data, which are in-situ observations collected from weather balloons, were also gathered. These radiosonde observations served as ground truth data for validating the quality of atmospheric profiles obtained from the GNSS RO technique. By comparing the GNSS RO profiles with the radiosonde data, the accuracy and reliability of the RO technique could be assessed.

2.2 Appraisal of GNSS RO Technique and Validation of Atmospheric Profiles

To understand the practicability of the GNSS RO technique in observing the atmosphere over Nigeria, the study appraised the GNSS RO technique itself, including the different missions associated with it. The coverage and distribution of events from various RO missions over Nigeria were examined. It was observed that the coverage of RO missions varied considerably, depending on the orbit design of both the GNSS and low earth orbiting satellites. This appraisal provided insights into the strengths and limitations of the GNSS RO technique in capturing atmospheric data over the Nigerian region.

The quality of the atmospheric profiles obtained from the COSMIC mission was validated by comparing them with available radiosonde observations in the Nigerian region. Statistical analysis techniques were employed to evaluate the agreement between the GNSS RO-derived profiles and the radiosonde data. Parameters such as temperature, pressure, refractivity, and vapor pressure profiles were compared. Absolute mean errors were calculated to quantify the differences between the GNSS RO and radiosonde measurements. The validation process helped to assess the accuracy and reliability of the GNSS RO technique in capturing atmospheric conditions in the Nigerian region.

2.3 Derivation of Climate Change Indicators and Comparison with Ground-Based Measurements

The study derived two prominent climate change indicators, namely tropopause height (TH) and precipitable water vapor (PWV), from the COSMIC profiles over Nigeria. By analyzing the seasonal patterns of TH and PWV, the variations and relationships with atmospheric conditions in different seasons of the Nigerian region were investigated. This analysis provided insights into the dynamics and trends of these climate change indicators, highlighting their importance in understanding the atmospheric processes and climate variations in Nigeria.

To assess the agreement and consistency of the derived TH and PWV values, they were compared with ground-based GNSS measurements and radiosonde observations. This comparison allowed for an evaluation of the reliability of the GNSS RO-derived values. The range of differences between the GNSS RO-derived values and ground-based measurements was calculated, providing a measure of the level of agreement between different measurement techniques. This comparison provided additional confidence in the accuracy and usefulness of the GNSS RO technique for atmospheric and climate research in Nigeria.

3.0 Results and Discussion

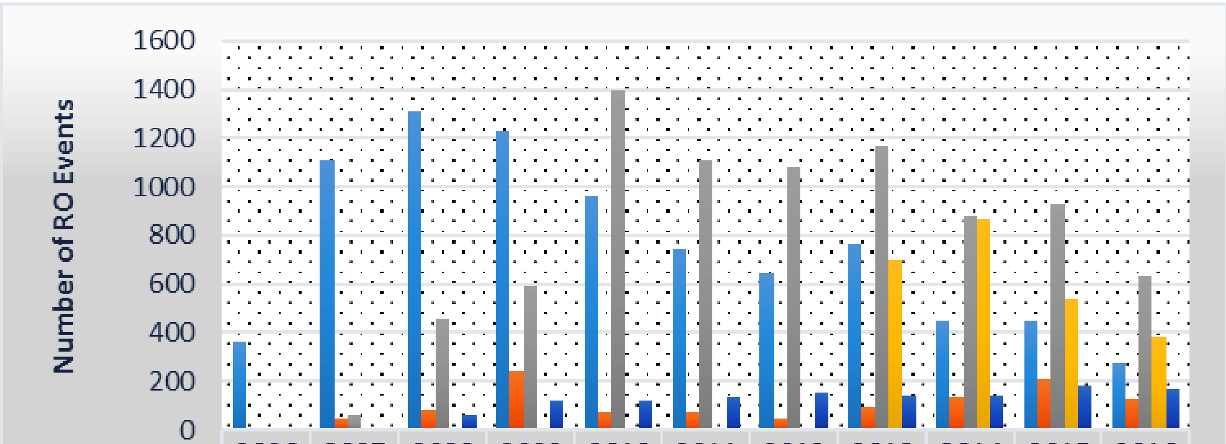
The evaluation of GNSS Radio Occultation (RO) technology for meteorological and climate applications over Nigeria holds significant importance in addressing the challenges posed by the sparseness or non-existence of conventional ground in-situ observations in the sub-Saharan African region. This study aims to assess the practicability of the GNSS RO technique in observing the atmosphere over Nigeria and its potential for meteorological and climatic research. To achieve this goal, the GNSS RO technique and its various missions, as well as the distribution of events from different RO missions over Nigeria, were thoroughly examined. The coverage of the RO missions was found to vary considerably, dependent on the orbit design of both the GNSS and the low earth orbiting satellites.

Furthermore, the quality of atmospheric profiles obtained from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission was validated against available radiosonde observations in the Nigerian region. The validation results demonstrated a strong agreement between the COSMIC profiles and the radiosonde data, with low absolute mean errors for temperature, pressure, refractivity, and vapor pressure profiles. Additionally, two prominent climate change indicators, namely tropopause height (TH) and precipitable water vapor (PWV), were derived from COSMIC profiles over Nigeria. The results revealed distinct seasonal patterns in the GNSS RO-derived TH and PWV, effectively describing the atmosphere and seasons of the Nigerian region. These findings were consistent with radiosondes and ground-based GNSS measurements.

Considering the anticipated improvements and follow-on missions for GNSS RO, it is expected that the quantity and quality of occultation events will increase in the Nigerian region. Consequently, the GNSS RO technique will become an indispensable tool for future operational atmospheric and climate research in Nigeria and the broader sub-Saharan Africa region. In the following section, the results and discussions will delve deeper into these findings, providing a comprehensive analysis of the observed data and their implications for meteorological and climate applications over Nigeria.

3.1 Distribution of GNSS Radio Occultation Sounding Events over Nigeria

The number of RO events and their spatial and time distribution over the Nigerian territory from four (4) GNSS RO missions since 2006 is considered here. As of 2016, a general reduction in the number of annual occultation was observed over Nigeria as shown in Figure 3. The obvious reason for the reduction in number of RO events could be attributed to degrading satellites from the various missions, i.e., since 2011 after the decommissioning of the COSMIC constellation which had a mission life expectancy of 5-years. The number of RO events from the mission had been on the decrease but is intended to be continued in order to minimize data gaps until a follow-on constellation mission is be implemented. The GRACE mission has also exceeded its life expectancy but to also continue to provide observations until the GRACE follow up mission comes on board to minimize data gaps.



	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
COSMIC	362	1111	1311	1228	960	745	645	764	447	450	278
GRACE	0	44	78	244	73	76	48	91	137	208	125
METOP-A	0	58	456	591	1395	1110	1082	1169	881	927	632
METOP-B	0	0	0	0	0	0	0	696	868	538	386
TSX	0	0	62	124	122	132	153	139	142	182	166

Figure 3: Yearly distribution of GNSS RO from five missions over the Nigerian region

Conventionally, radiosonde observations are used for atmospheric profiling in many parts of the world, the accuracy measurement from radiosonde observations as an in-situ observation system is well documented and often used to validate other systems (Soden and Lanzante, 1996; Zipser and Johnson, 1998; Paukkunen et al., 2001; Elliott et al., 2002; Soden et al., 2004). However, the spatial and temporal distribution of radiosonde observations is a disturbing issue in Nigeria and many other African countries alike. Records from the Integrated Global Radiosonde Archive (IGRA) show very low data record for the region of Nigeria. Figure 4 shows the record of radiosonde stations around Nigeria. The IGRA is the most comprehensive record of radiosonde data in the world; they provide sounding-derived parameters at fixed observing stations on land that contain temperature observations and a surface pressure level.

The parameters include precipitable water vapour (PWV) between the surface and 500 mbar, the refractive index, vertical gradients of several variables, and various measures of boundary-layer characteristics and stability (Durre et al., 2006 & 2016). The IGRA record indicates that most of the radiosonde stations in Nigeria are not functional as only one station (WMO no: 65125) has few data records in recent times, other stations don't have data record is at least the last 25 years. In contrast, the daily number of RO events from each of the RO missions is at an average of about two (2) events from each mission, so looking at the COSMIC, MetOP-A, MetOP-B, GRACE and TerraSAR-X, one would expect about a maximum ten (10) RO events from the missions over Nigeria on a daily basis.

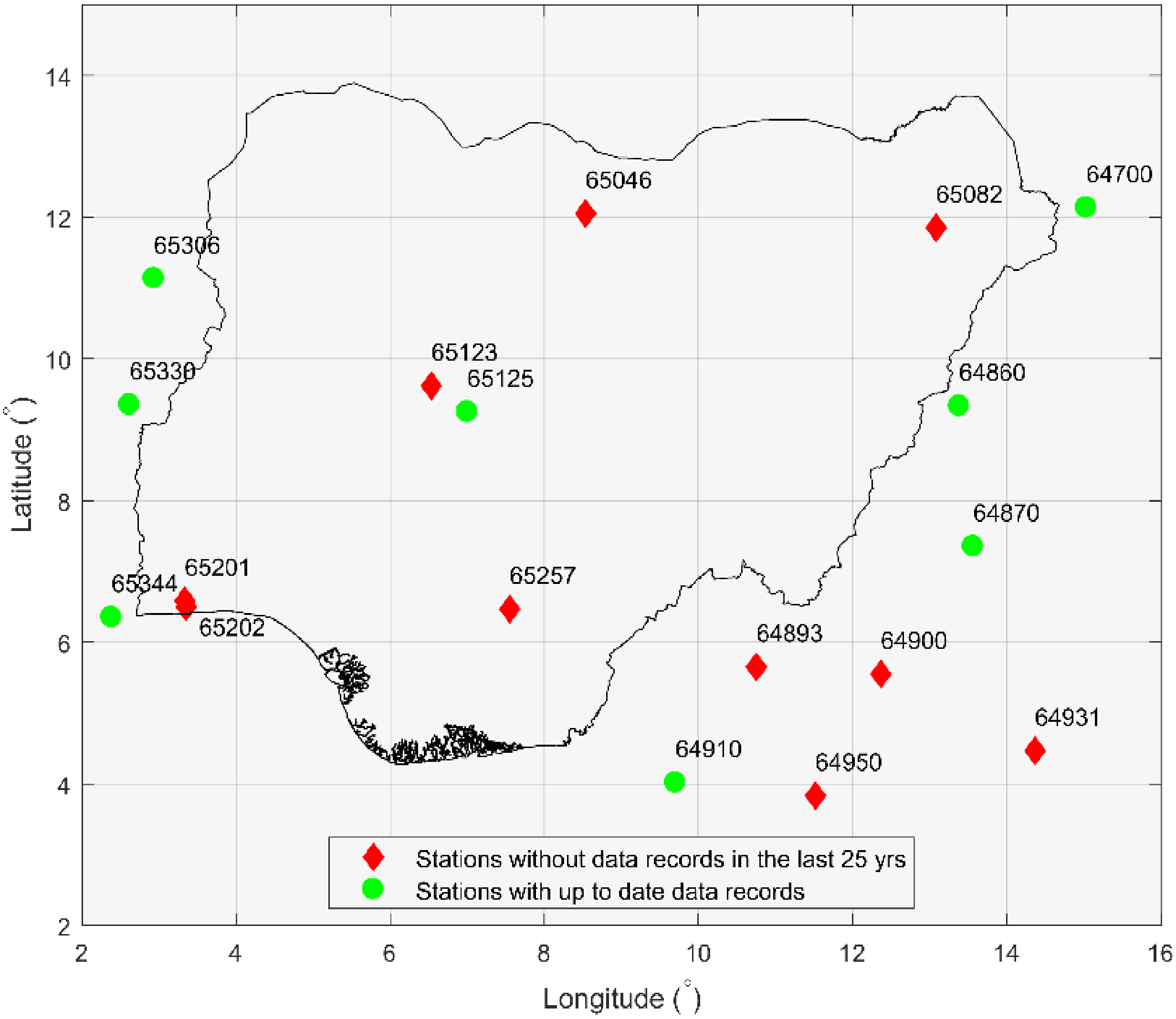


Figure 4: Distribution of Radiosonde stations (with WMO Id) around the Nigerian territory based on records from the international Global Radiosonde Archive(IGRA), stations with up-to-date data records are marked in green diamond symbol

Evidently, the number of daily RO events over Nigeria is small and this is clearly attributable to the orbit design of occulting LEO satellite(s) of the different RO missions, thus the number of RO events from the respective missions varies in the different parts of the world because orbit design of occulting LEO satellites often has specific region(s) of interest. However, GNSS RO technique show data superiority to the traditional radiosonde, the few RO events have big impact and are at better horizontal resolution, very high vertical resolution and give better spatial spread of observations than the radiosonde station which remain stationary at specific locations and thus limited because the network requires proper physical locations and easy accessibility. The Figure (5) shows the spatial distribution of RO events from the different missions under consideration for the period of a year (2016) over the Nigerian region, the spatial distribution of RO events from the individual missions is quite impressive as the most remote or inaccessible parts the Nigerian region are profiled. Obviously, the new atmospheric profiles from the respective and/or combined RO missions are an important source of information to Nigerian weather and climate studies; though the current daily rate of RO events might not be very appropriate for meteorological applications, however, continuous records obviously will definitely support climate monitoring better than the traditional radiosondes.

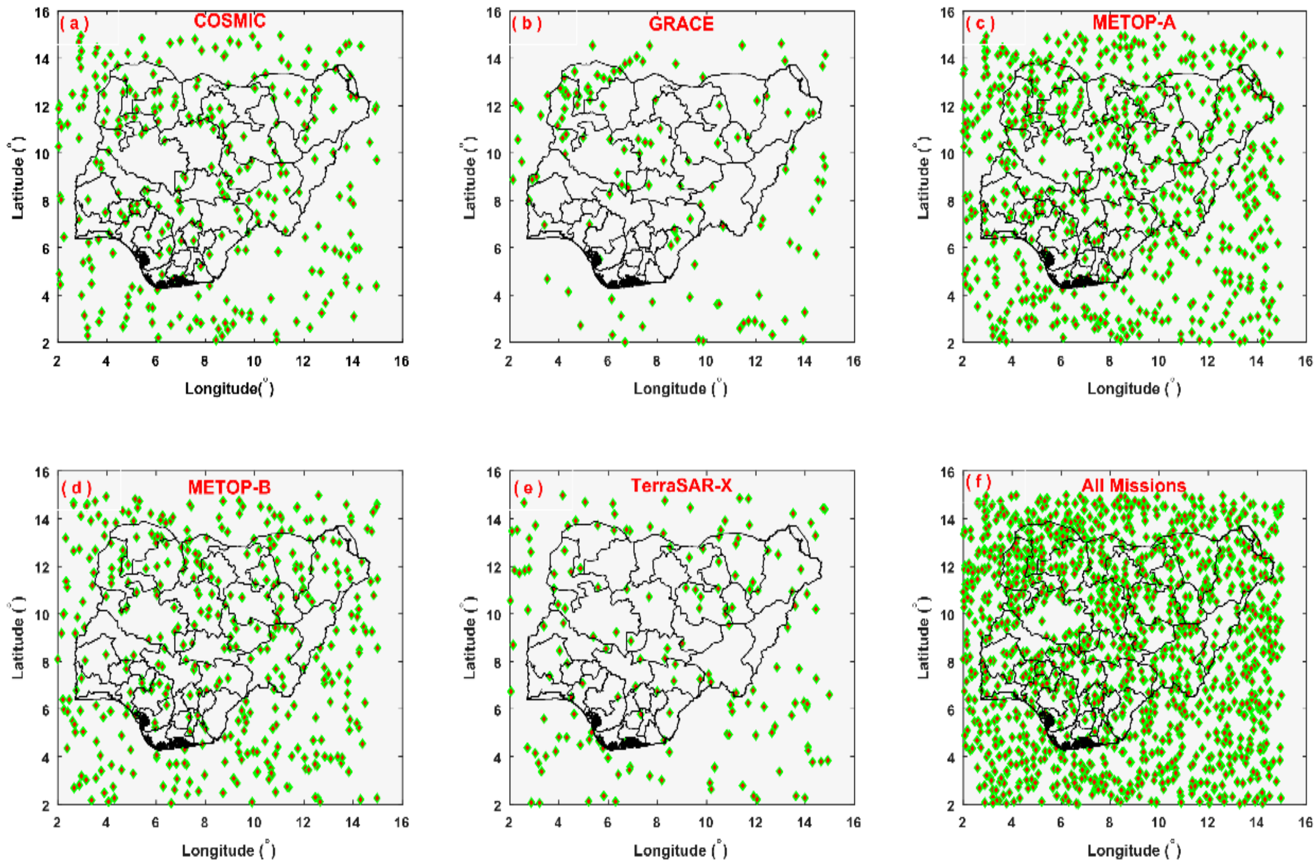


Figure 5: Spatial distribution of GNSS RO sounding profiles (in green dots) from (a) COSMIC, (b) GRACE, (c) MetOp-A, (d) MetOp-B, (e) TerraSAR-X and (f) All Missions (that is a-e) for the year 2016 over the Nigerian region

The GNSS RO data are accessible as single profiles comprising of bending angle, refractivity, temperature, pressure, and geopotential height in the altitude range up to 40 km for all RO missions processed at the COSMIC data analysis and archive centre (CDAAC). The horizontal resolution of is around 200 km with a less than 100 km horizontal drift at the height of its tangent point for each profile. The vertical resolution of each profile is ~100 m to 200 m in the lower troposphere and ~1400 m in the stratosphere. The temporal resolution is about +/- 4hrs for each profile and randomly distributed in space. The GNSS RO technique currently provides superior (vertical, horizontal and temporal) resolutions for atmospheric observations when compared to other satellite sounders (Wickert, 2016). This ongoing quality dataset has been invaluable for many aspects of atmospheric studies. Climate-related studies rely on high-resolution atmospheric observations. Studies have demonstrated the potential of GNSS RO profiles for characterizing troposphere structures and changes (Son et al., 2011; Liu et al., 2014). For other examples, the global gravity wave signatures in the upper troposphere and stratosphere can be obtained from GNSS RO profiles (Alexander et al., 2008; Torre et al., 2009). Studies of atmospheric waves, turbulences and tides have been carried out using GNSS RO data (Zeng et al., 2008; Cornman et al., 2009).

It is expected that improvements in GNSS RO missions will come with better data coverage for Nigeria. It is expected the next generation RO mission will carry multi-GNSS receivers or payloads; perhaps increasing the number of transmitting and receiving satellites will significantly improve the coverage and horizontal resolution of the RO observations over Nigeria; also, using new signals with more transmission power will increase the GNSS; Signal-to-Noise ratio, consequently improving the RO retrieval process in the lower atmosphere. RO is likely to be a dominant source of information for climate monitoring as the coverage and time series lengthens.

Although, the application of the GNSS RO technique for climate monitoring and studies is well discussed, yet a detailed comparison of all its retrieved parameters with independent reliable techniques over the different regions of the world is indispensable. Thus, next, we discuss results from Nigeria demonstrating the potential of RO technique in meteorological and climate applications over Nigeria.

3.2 Demonstrating the potential of GNSS RO for Meteorological and Climate related applications

From the preceding section of this is paper it was established that the GNSS RO technique offers potential dataset for meteorological and climate applications over Nigeria. To demonstrate the potential of RO dataset in meteorological and climate applications over the Nigerian region, we look at three sets of applications in this section. Firstly, essential variables from the RO mission are compared with radiosonde estimates; secondly, we demonstrate the potential of estimating and analysing the tropopause structure from RO profiles and lastly, we a look at the atmospheric water content variables from RO observations.

COSMIC post-processed data are used for all discussions in this section. 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, the time period varies for the different analysis under this section but lies between 2006 and 2016.

3.3 Evaluating Atmospheric Profiles from GNSS RO

The Figure 6 depicts a COSMIC RO event that was captured by COSMIC-C002 satellite at GPS time 02:39:00 on 28 June 2012. The captured RO event is at a distance of about 99.79 km from the radiosonde launch site in Ndjamena (WMO No: 64700) in the Chadian territory just some few kilometres from the Nigerian border. The radiosonde data was archived as IGRA Version 2 product which consists of quality-controlled radiosonde observations of temperature, humidity, and wind at stations across all continents. The Figure 6 clearly portrays the superior vertical resolution of GNSS RO over the other sounding technique, the atmospheric profiles from the radiosonde observations are typically at a maximal height of 30 km. The atmospheric profiles from GNSS RO have their core region between height intervals of about 5-35 km.

To further exploit or verify the effectiveness of the profiles of temperature, pressure, refractivity, and water vapour pressure in the atmosphere over the Nigerian region from COSMIC, we collected COSMIC RO data at two epochs in 2012 and 2016, each of the epoch consists of five (5) RO events occurring during that year at distances not greater than 200 km from the radiosonde launch at Ndamena (WMO No: 64700). These COSMIC RO events are given in Table 2. The ten (10) GNSS RO events were collected as wetPrf files in Network Common Data Form (NetCDF) format, the quality flag in all the ten (10) events indicated “bad=0” implying that all passed the quality control successfully.

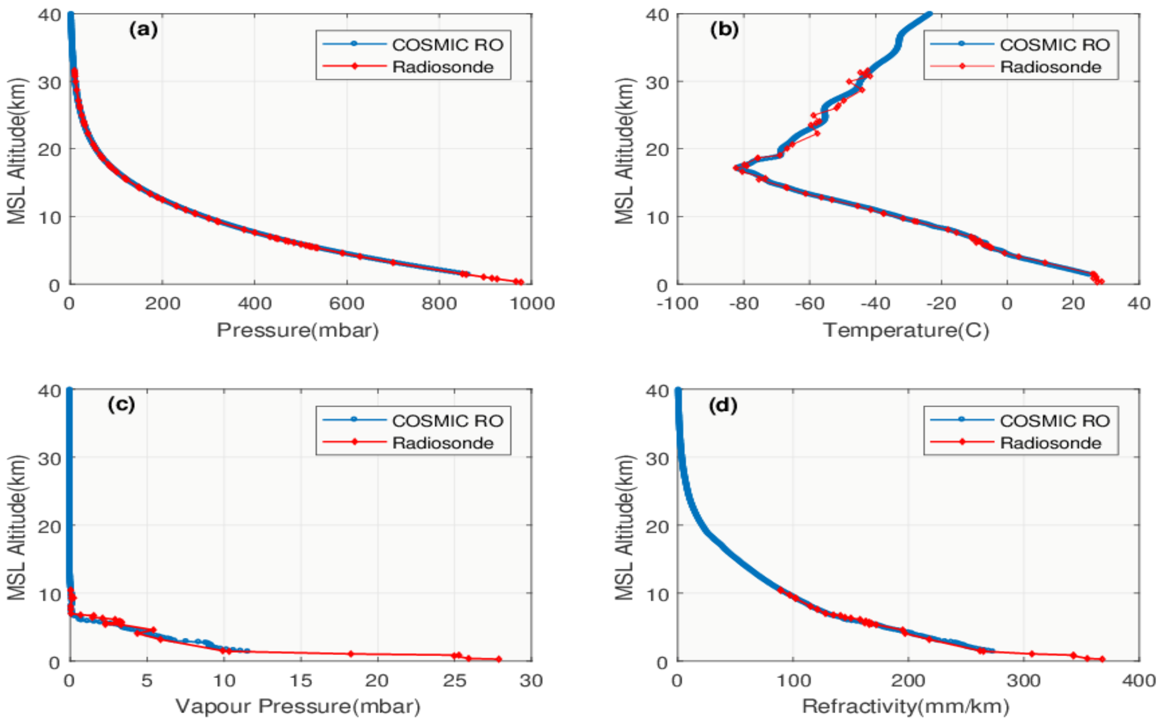


Figure 6: Atmospheric profiles from FORMOSAT/COSMIC mission and in-situ radiosonde observation at Ndjamena (WMO:64700) (a) is the pressure profiles, (b) is the temperature profiles, c) is the water vapour pressure profiles , d) is the refractivity profiles.

Table 2: COSMIC RO event near radiosonde launch site (WMO No: 64700)

Date	Longitude (°)	Latitude (°)	COSMIC RO Events
		Epoch 1	
11 January 2012	14.015	12.978	C001.2012.011.14.13.G10
15 February 2012	14.665	13.061	C006.2012.046.14.44.G01
28 June 2012	14.115	12.059	C002.2012.180.02.39.G08
4 July 2012	14.619	13.787	C002.2012.186.12.24.G14
03 October 2012	14.720	12.549	C002.2012.277.08.55.G15
		Epoch 2	
10 May 2016	15.946	12.077	C001.2016.131.07.58.G15
30 June 2016	15.168	13.836	C002.2016.182.19.45.G09
9 July 2016	15.068	13.943	C001.2016.191.11.00.G15
11 July 2016	14.889	11.830	C001.2016.193.19.08.G28
26 July 2016	15.249	12.997	C001.2016.208.18.50.G32

The COSMIC atmospheric profiles were at different vertical resolutions with the radiosonde. So, MATLAB interpolation code utilizing the '*interp1*' function was used to interpolate the height of profiles of temperature, pressure, refractivity and water vapour pressure from COSMIC GNSS RO to the same height as those of the radiosonde to enhance the comparison of the two. The height of the radiosonde profile typically ranges from 0.295km to about 30km. To avoid extrapolation errors, profiles from COSMIC that are less than the original height from the COSMIC file are excluded from the results of the interpolation. The Figures 7 and 8 depict the difference between profiles of temperature, pressure, refractivity, and water vapour pressure at the respective common heights of the profiles for the two epochs (2012 and 2016).

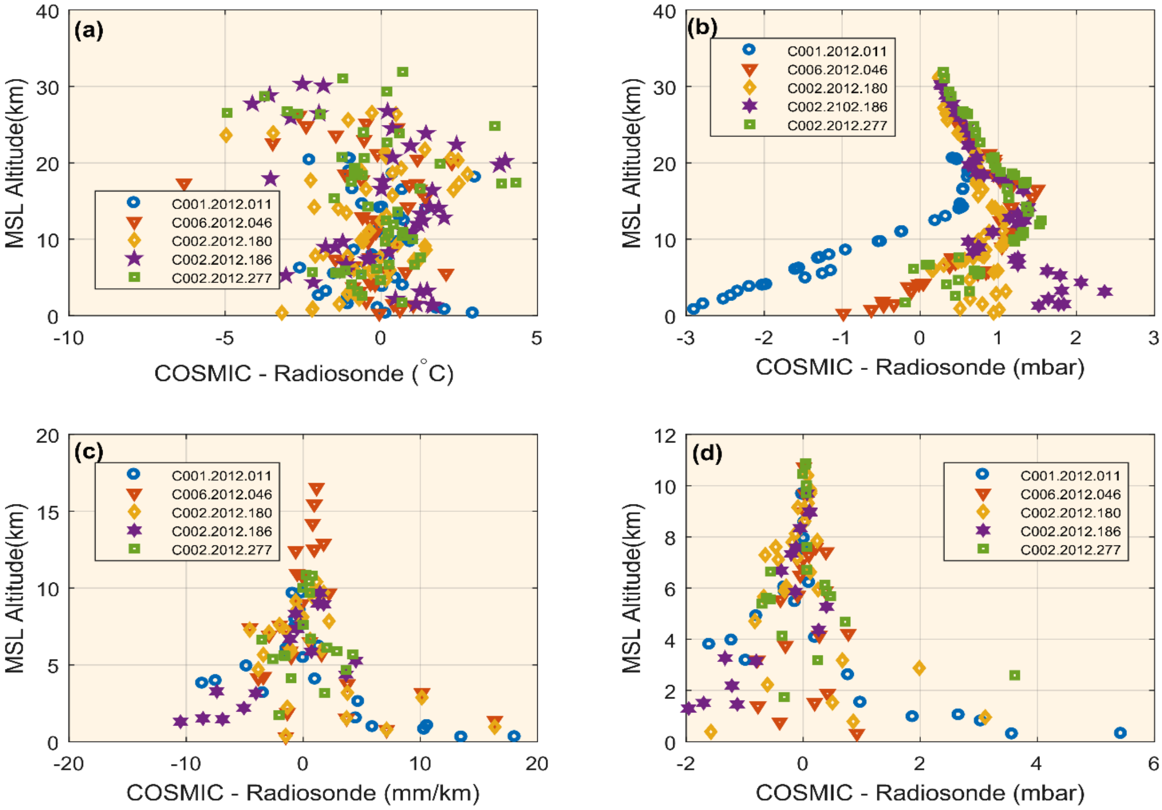


Figure 7: The differences between a) temperature, b) pressure, c) refractivity, and d) water vapour pressure from FORMOSAT-3/COSMIC RO and radiosonde against the altitudes in 2012

From Figures 7 and 8, it is evident that the differences in temperature profile between COSMIC and radiosonde are larger than that of the other profiles (pressure, refractivity, and vapour pressure). There was no clear pattern as to the difference between the COSMIC and radiosonde data; the differences range from -5.79 to +5.76 Celsius. There were more negative differences which indicate that radiosonde reports hotter temperature over the region. A look at the pressure profiles gives a result quite different from that of the temperature profile. From Figures 7 and 8, the differences between the pressure estimates along the profile seem to converge toward zero with an increase in altitude. Thus, larger pressure differences between the two datasets in the troposphere are found when compared with those in the stratosphere. The differences in pressure estimates along the profile range from -2.89 to +2.9787 mbar. The results of the refractivity and water vapour pressure are quite promising and have a very clear pattern; it can be seen from the Figures 7&8 that the agreement between COSMIC and radiosonde refractivity and water vapour pressure profiles is stronger at an altitude greater than 7km. A more general look at all the profiles can further reveal that COSMIC profiles don't agree with radiosonde profiles at a very low altitude of less than 7-10 km, this observation corroborates the fact GNSS RO profiles are not suitable low troposphere studies. The results from the various comparisons are evident in the quality of observations from the GNSS RO technique. However, a more comprehensive comparison test may be required which is out the scope of the current paper.

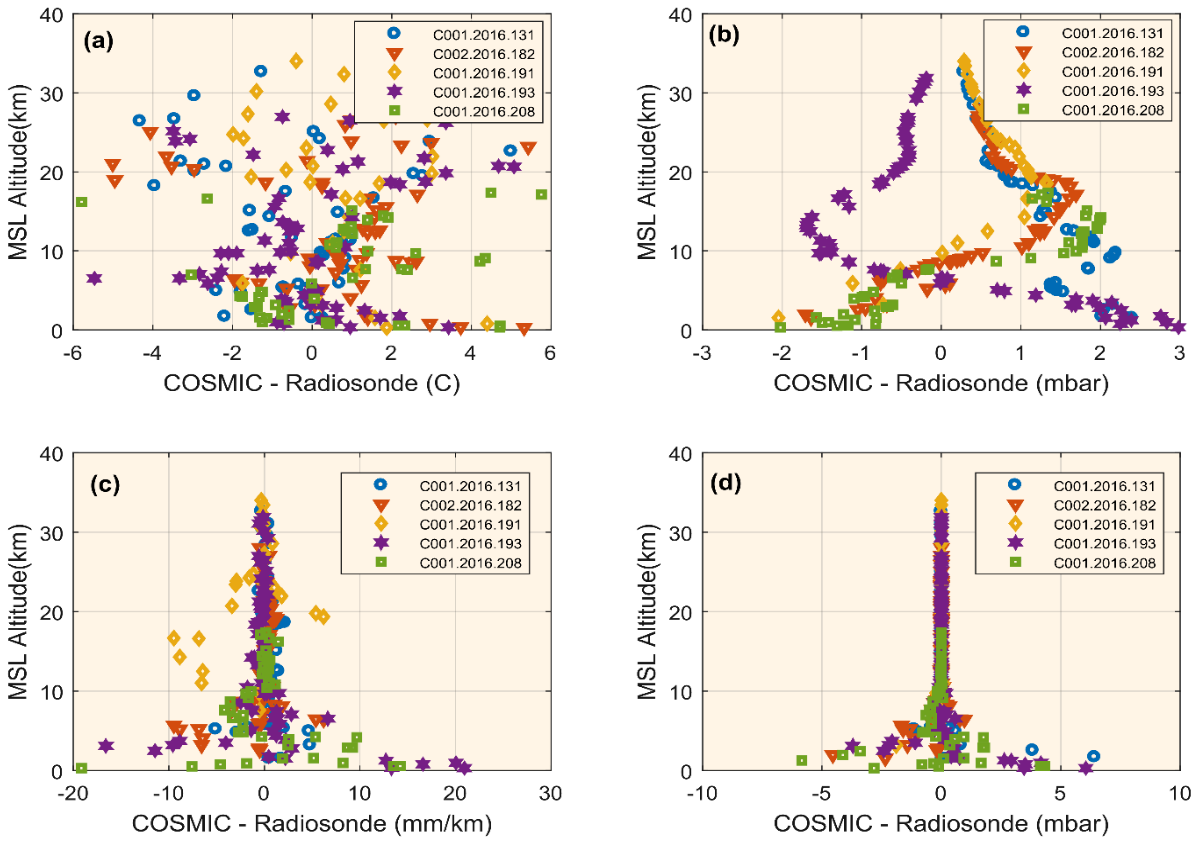


Figure 8: The differences between a) temperature, b) pressure, c) refractivity, and d) water vapour pressure from FORMOSAT-3/COSMIC RO and radiosonde against the altitudes in 2016

The distribution of the combined differences between the two epochs of 2012 and 2016 for the COSMIC and radiosondes observations is depicted in Figure 9. The absolute mean value for the temperature difference was estimated at 1.42 $^{\circ}C$ with a standard deviation of 1.21 $^{\circ}C$. The pressure profiles showed a better agreement between the observing systems than that of the temperature profiles. The absolute mean value and standard deviation of the residuals stood at 0.97 and 0.58 mbar, respectively. Figure 9 is also able to reveal that pressure value is higher from COSMIC for most of the height profiles. It can be seen in Figure 9 that the refractivity and water vapour pressure profiles agreed well with each from the COSMIC and radiosondes observations, the frequency of near zero differences or residual were very high and thus clearly demonstrates the efficacy of the observing systems.

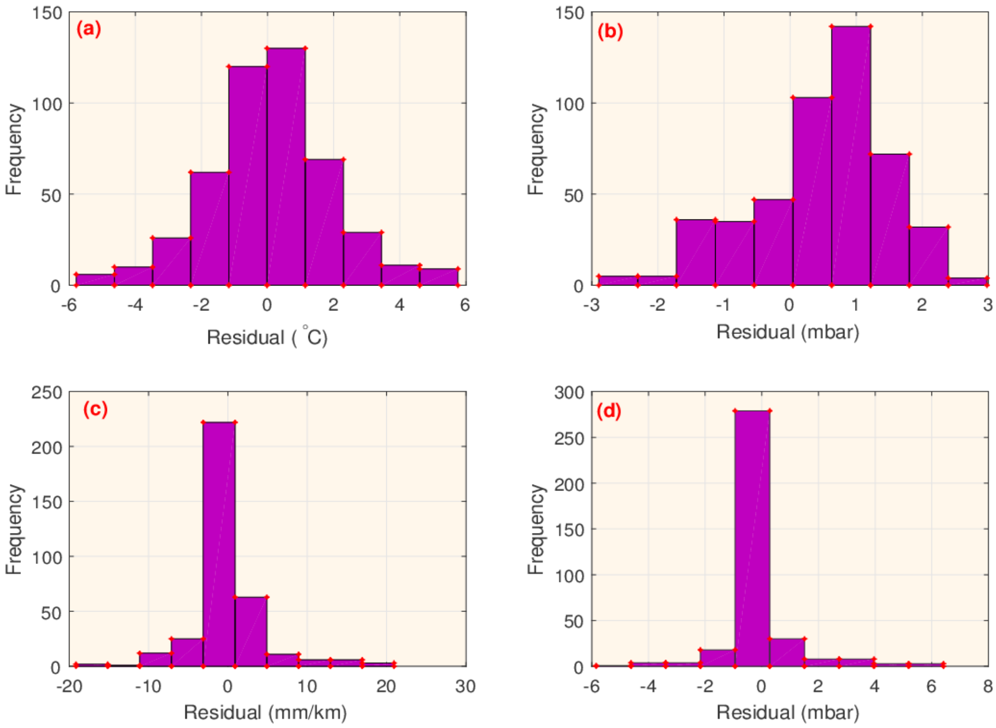


Figure 9: Frequency plot of residuals of between COSMIC and radiosonde atmospheric Profiles, a) is the temperature, b) pressure, c) refractivity, and d) water vapour profiles

3.4 Evaluating Tropopause height information from GNSS RO

Here we present discussions on the structure of the tropopause over Nigeria as derived from GNSS RO observations from the COSMIC mission. The tropopause, lying between troposphere and stratosphere, attracted increasing consideration recently. Its properties serve as a hint of climate change. The tropopause plays a key role in the upper troposphere and lower stratosphere (UTLS) by affecting chemical tracers exchange. The World Meteorological Organisation (WMO) (1957) has defined the tropopause as "the lowest level at which the lapse rate decreases to $2K/km$ or less, provided that the average lapse rate between this level and all higher levels within 2 km does not exceed $2K/km$", which is also known as thermal tropopause. The lapse rate is calculated using the following relation;

$$\delta T_i = (T_{i+1} - T_i)/(H_{i+1} - H_i) \qquad (2)$$

In the equation (2), T and H represents the temperature and altitude respectively of individual RO profile at specific pressure level. Starting from lower to higher altitude levels at the first point where $dT/dH > -2K/km$ and the average lapse rate between this level and all higher levels within 2 km does not fall below $-2K/km$ is the tropopause height.

The thermal definition of the tropopause was adopted to determine the tropopause height using COSMIC observations. To avoid unrealistically high or low tropopause heights and to increase computational speed, the search range for the algorithm is limited to between 550 hPa and 75 hPa (approx. 5–18 km). If the calculated tropopause exceeds one of these limits, the result is rejected. Based on this condition, a total of 1223 profiles of occultation events from the COSMIC mission for the period of 2013-2016 were processed. To investigate seasonal variations in tropopause height, the RO events 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). The Figure (10) presents the seasonal estimates of the tropopause height over the Nigerian region from COSMIC observations for the period of 2013-2016.

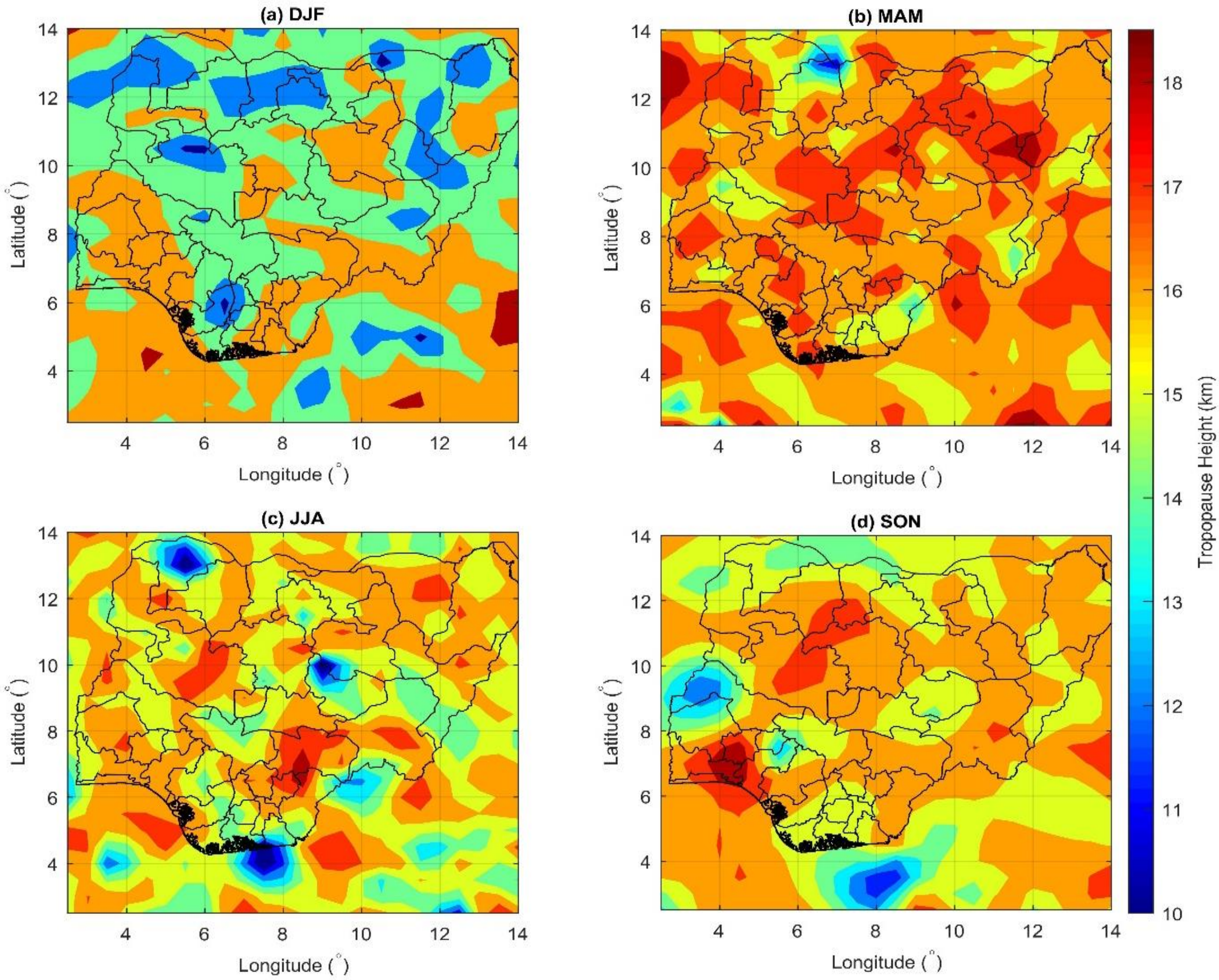


Figure 10: Seasonal mean tropopause height, a) DJF, b) MAM, c) JJA, c) SON derived from COSMIC for the period of 2013-2016

The Figure (10) shows a clear seasonal variation in tropopause height within 10-18km with highest values during MAM. The months of March, April and May (MAM) are the hottest in the north, with few records of rain in the southern part of Nigeria. The average tropospheric temperature controls the tropopause height. This accounts for the high tropopause heights in the summer (MAM). The lowest tropopause height values were recorded in DJF, during this season, the northern part of Nigeria is dry with very low temperature because of the Harmattan, while the south is also dry and humid. Also, from the Figure (10), high tropopause values were reported in JJA, though much lower than MAM and higher than in SON. The peak of the wet season in all parts of Nigeria is in the months of June, July and August (JJA). The months of September, October and November (SON) signify the end of the wet season in the north, while in the south, it is a period often characterised by scanty rains and severe thunderstorms. From the foregoing, it is evident that there is a high variation in solar illumination through the year over Nigerian region and the GNSS RO technique is able to map the variations in solar illumination as represented in the tropopause height variation over the region. To further ascertain the efficacy of the results from the RO technique, we computed the tropopause height utilising datasets (temperature and geopotential height) from a numerical weather model (ERA-Interim) of the European Centre for Medium weather forecast (ECMWF) (De et al., 2011). The monthly temperature and geopotential height from the ERA-Interim was obtained from http://apps.ecmwf.int/dataset/data/interim-full-monthly/ and the tropopause height was computed using the thermal definition as presented herein. The Figure (11) presents the seasonal estimates of the tropopause height over the Nigerian region from ERA-Interim dataset for the period of 2013-2016.

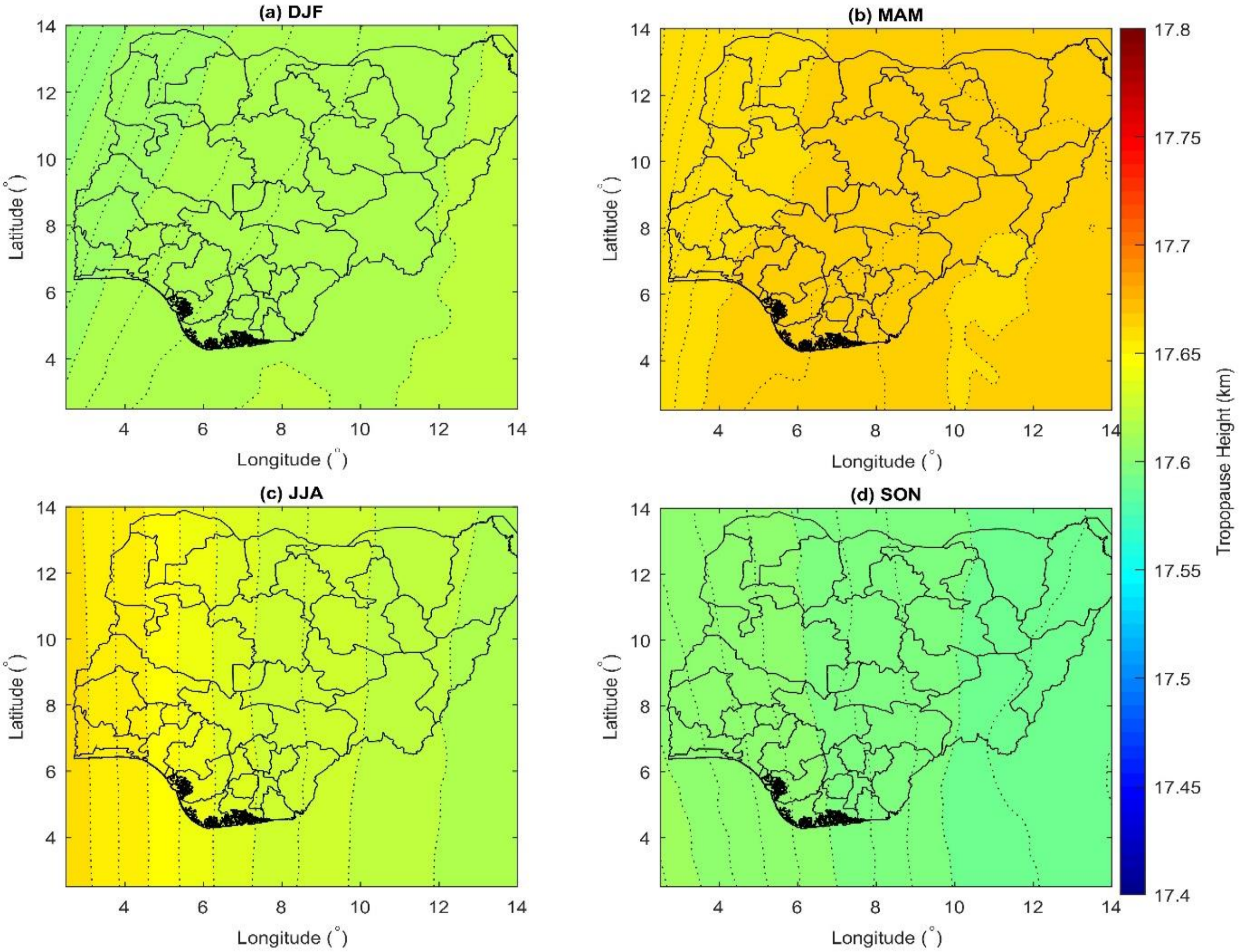


Figure 11: Seasonal mean tropopause height, a) DJF, b) MAM, c) JJA, d) SON derived from ECMWF for the period of 2013-2016 over the Nigerian region

A comparison of the seasonal pattern of GNSS RO and Era-Interim from Figures ((10) and (11)) reveals a similar cyclic behaviour across the different seasons, however, it can be seen that in terms of the averaged seasonal variations, the Era-Interim tropopause height doesn't show any significant variation over Nigeria. The estimated tropopause from the Era-Interim is typically about 17km. The difference in the tropopause height between ERA-Interim and GNSS RO can sometimes times be larger than 5km and this layer difference may arise due to the low change in vertical temperature gradient. This low variability in temperature gradient leads to the higher/lower tropopause heights than actual tropopause height. Overall, GNSS RO captures the variability in the vertical temperature gradient better.

To ascertain the agreement between GNSS RO derived tropopause height and that from radiosonde, we found and calculated the difference between the duo techniques for occultation events at a maximum distance of 200km from the radiosonde site (WMO no: 64777). It would have been ideal to consider more radiosonde sites to gain a more comprehensive insight into the variation and trend of the tropopause as observed by the duo, we are constrained by availability of sounding observations from radiosondes in the region. The summary of the result is presented in Table 4 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 3: Difference in estimated tropopause height from COSMIC and radiosonde observations

COSMIC RO Events & (Date)	Longitude of occultation event $(^\circ)$	Latitude of occultation event $(^\circ)$	Tropopause height (km)		
			COSMIC	Radiosonde	Difference
Epoch 1					
C001.2012.011.14.13.G10 (11 January 2012)	14.015	12.978	17.550	14.425	3.125
C006.2012.046.14.44.G01 (15 February 2012)	14.665	13.061	16.894	15.405	1.489
C002.2012.180.02.39.G08 (28 June 2012)	14.115	12.059	15.650	16.165	-0.515
C002.2012.186.12.24.G14 (4 July 2012)	14.619	13.787	15.850	16.085	-0.235
C002.2012.277.08.55.G15 (03 October 2012)	14.720	12.549	17.050	15.745	1.305
Epoch 2					
C001.2016.131.07.58.G15 (10 May 2016)	15.946	12.077	14.850	16.825	-1.975
C002.2016.182.19.45.G09 (30 June 2016)	15.168	13.836	17.050	10.485	6.565
C001.2016.191.11.00.G15 (9 July 2016)	15.068	13.943	16.750	16.585	0.165
C001.2016.193.19.08.G28 (11 July 2016)	14.889	11.830	15.150	14.885	0.265
C001.2016.208.18.50.G32 (26 July 2016)	15.249	12.997	15.550	16.385	-0.835

As a final point, though the foregoing discussions were based on a single GNSS RO mission. The determined tropopause heights from COSMIC data and its agreement with in-situ observations from radiosonde over the Nigeria region clearly demonstrate the significance and the great potential of the GNSS RO technique. These results indicate that the GNSS RO derived tropopause height is a strong climate fingerprint and can be used for the observation of different trace constituents within the troposphere and also give a better understanding of the transition region between the troposphere and stratosphere over the Nigerian region.

3.5 Evaluating Atmospheric water vapour information from GNSS RO

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. 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. One of the most valuable attributes of ground-based GNSS-PWV is the ability to provide high temporal and accurate PWV estimates under all weather conditions, including cloud cover and precipitation. The accuracy of the ground-based GNSS meteorology is well documented in Nigeria and other regions/ countries in the world (Isioye et al., 2017 and references therein).

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 equation (1) using the following relations;

$$ZTD = \int_{l}^{r} (n-1) ds = 10^{6} \int_{l}^{r} N ds \tag{3}$$

In the discrete form, the equation (3) can be written as;

$$ZTD \approx \sum_{p}^{r} \left(\frac{N_{i+1} + N_{i}}{2} \right) \cdot \Delta s_{i} \tag{4}$$

In equation (4), 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 as shown in Figure (13). The ZTD estimates as presented in the Figure 13 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.

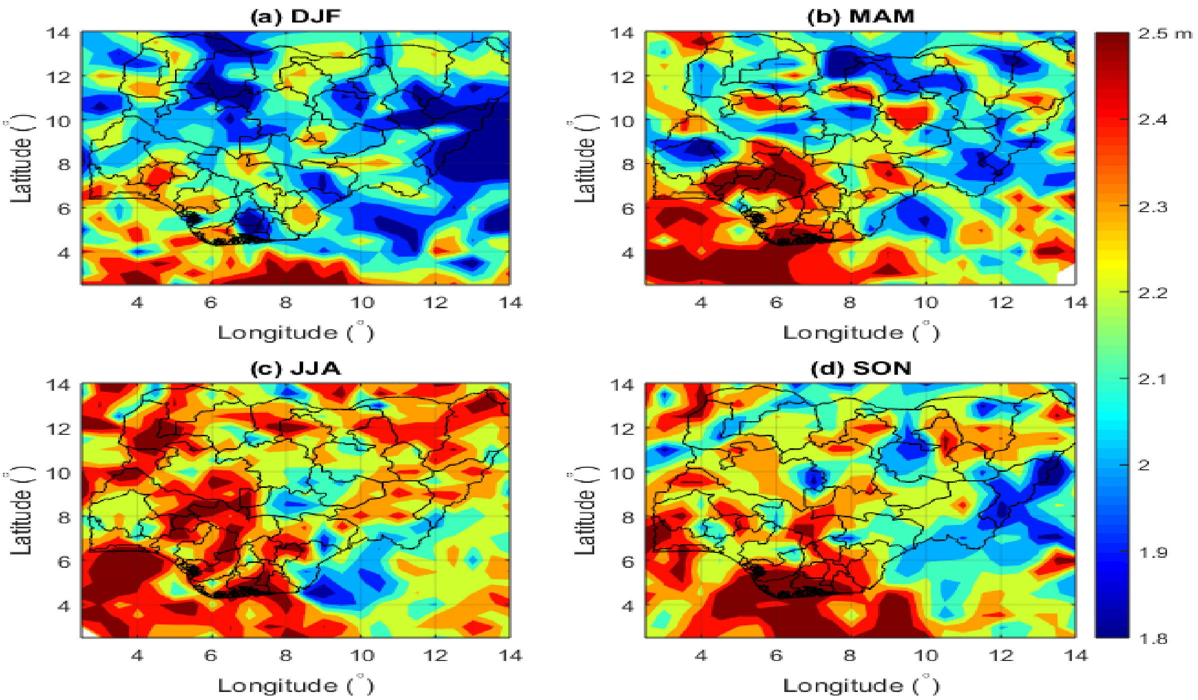


Figure 13: Seasonal mean ZTD, a) DJF, b) MAM, c) JJA, c) SON derived from COSMIC for the period of 2013-2016 over the Nigerian region

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 (5),

$$ZHD = 0.002277 \times \left[\frac{P}{1 - 0.00266\cos(2\phi) - 0.28 \times 10^{-6} \times h} \right] \quad (5)$$

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 (6) to estimate the PWV for each occulting event. Equation (6) is suggested to users as a handy formula to estimate PWV (in mm) in Nigeria using $T_s\,(K)$ and ZWD (mm) as inputs.

$$PWV = ZWD \times \left[9.80392 - \frac{16917.64}{0.053499T_s + 1739.07624} \right]. \quad (6)$$

Again, PWV estimates were grouped into seasonal means. The Figure 14 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. To validate the PWV estimates from the occultation technique we utilize ground-based GNSS reference stations derived PWV. At present, the office of the Surveyor General of the federation (OSGOF) controls and fares a network of 15 continuously operating GNSS reference stations (frequently denoted to as the new Nigerian GNSS network [NIGNET]) in Nigeria (Jatau et al. 2010; Naibbi and Ibrahim 2014). These stations are primarily for surveying and positioning applications in Nigeria and are the backbone of the proposed Nigerian geocentric data (Dodo et al. 2011; Nwilo et al. 2013).

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. 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 (Saastamoinen 1972) with a Gauss–Markov power density of $2cm/hour^{1/2}$.

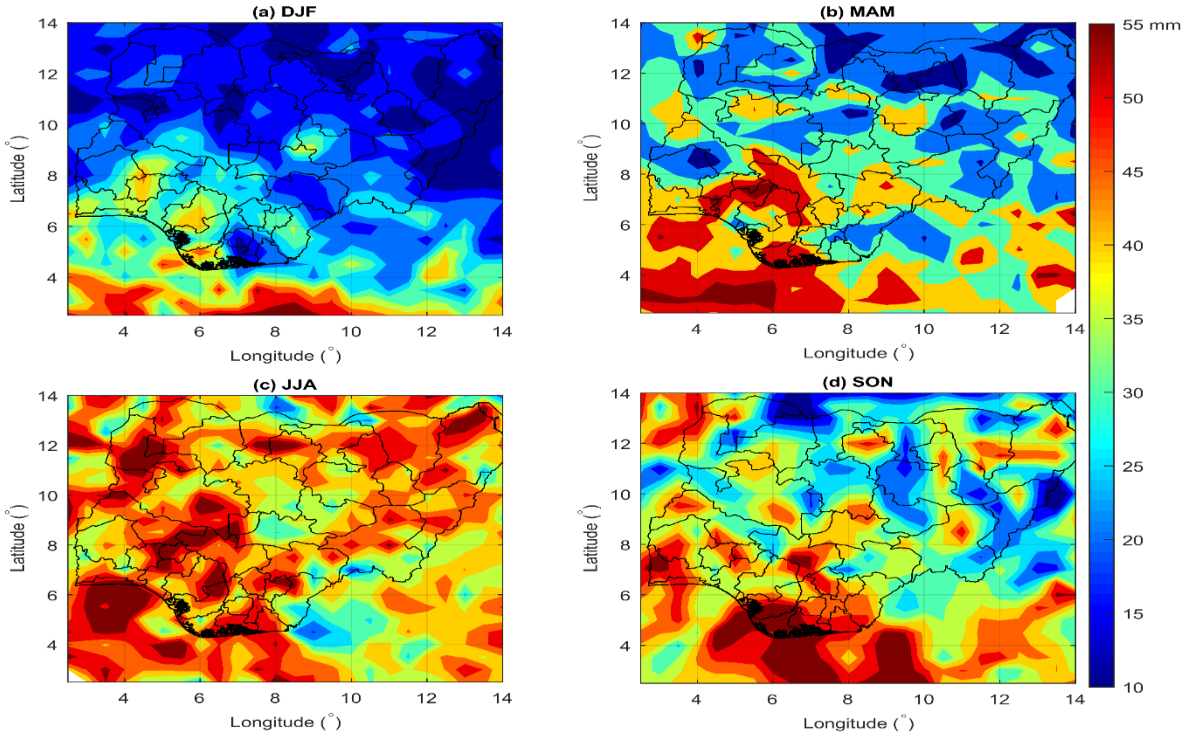


Figure 14: Seasonal mean ZTD, a) DJF, b) MAM, c) JJA, c) SON derived from COSMIC for the period of 2013-2016 over the Nigerian region

The 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 0.2 m, 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 (6):

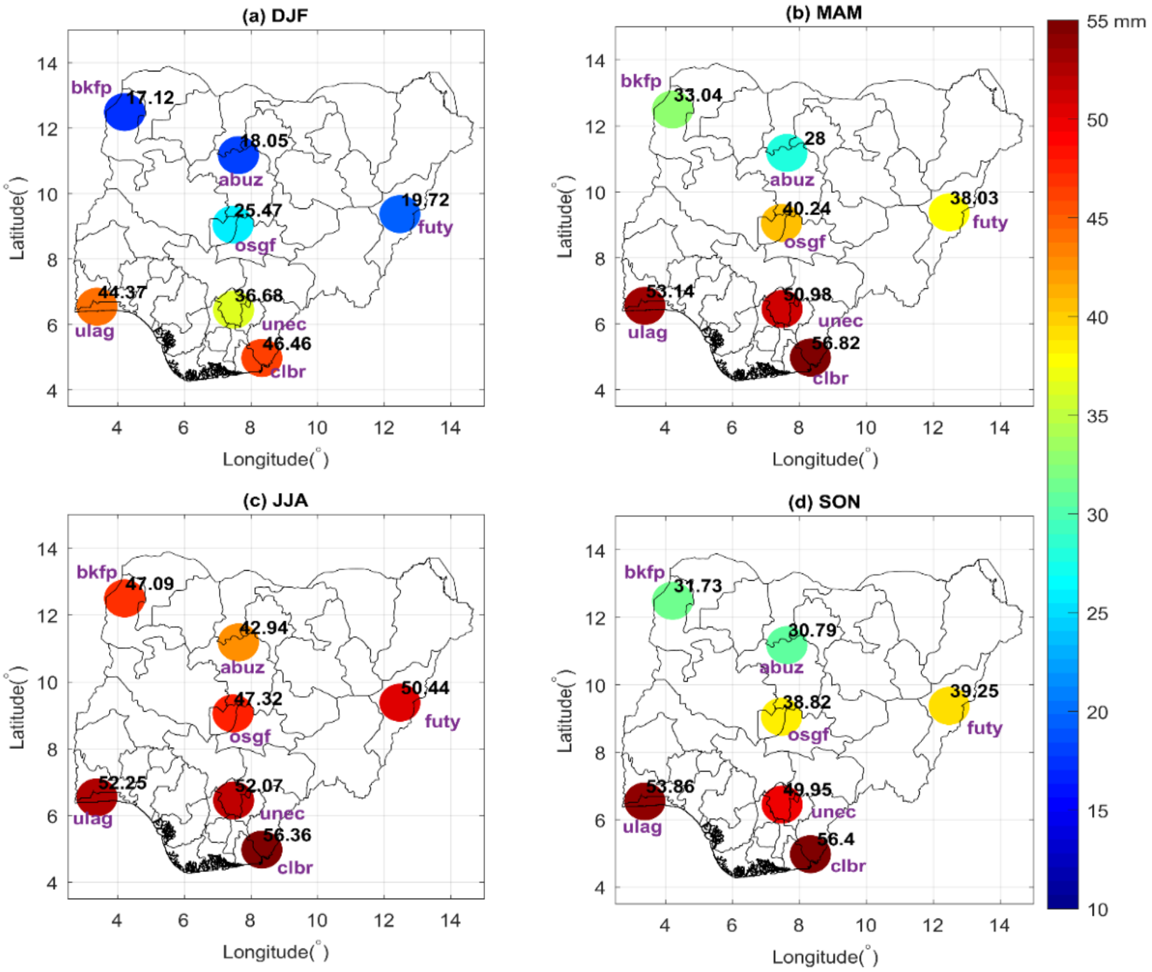


Figure 15: Seasonal mean ZTD, a) DJF, b) MAM, c) JJA, c) SON derived from COSMIC for the period of 2013-2016 over the Nigerian region

Figure 15 presents the PWV values for the four seasons. According to Figure 15, the seasonal PWV confirms an apparent variation with those in figure 14 for the GNSS RO. Both Figures 14 and 15 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. From the Figures 14 and 15, 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 15 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 also 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 4 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 4: Mean absolute difference of precipitable water vapour (PWV) estimates from GNSS RO and ground-based GNSS over Nigeria

Ground GNSS Station	Number of COSMIC Occultation Events (<100km from Ground-based GNSS Station)				Mean Difference (COSMIC – Ground GNSS Station) (mm)			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
abuz	3	2	2	-	1.323	4.425	4.655	-
bkfp	4	2	2	3	2.235	0.400	5.576	2.459
clbr	-	1	3	3	-	3.94	0.577	0.580
futy	3	2	4	2	2.283	0.895	2.668	1.245
osgf	1	2	4	-	0.800	2.355	1.052	-
unec	1	2	4	3	6.47	0.995	0.623	0.403
ulag	5	3	4	4	4.973	1.687	0.700	2.425

From the Table 4, 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.

3.6 Recent and Future GNSS RO Missions and Outlooks

Through a number of experimental missions and related studies since 1995, GNSS RO has demonstrated many advantages over other atmospheric observation methods. The GNSS RO recent and future/planned missions are expected to make a very valuable contribution to operational meteorology and climate studies. The Gravity Recovery and Climate Experiment Follow-On mission which provides the opportunity to establish the first-ever in-space inter-satellite laser ranging interferometer (LRI) is a successor of the GRACE mission that was decommissioned recently. Launched in May of 2018, The GRACE-FO observatory develops on the design of the original GRACE satellites, however, it has increased complexity due to the incorporation of the laser ranging interferometer and the integration of a number of enhancements based on lessons learned, leading to an overall more robust implementation (Kornfeld *et al.*, 2019).

A COSMIC follow-on mission, COSMIC-2, jointly managed by NOAA and Taiwan's National Space Organization (NSPO) was launched on 25 June 2019. With six LEO satellites in 24° inclination orbits, COSMIC-2 will collect at least 5,000 RO soundings per day from the GPS, Galileo, GLONASS satellite navigation systems over the tropics and subtropics from 35°N to 35°S, providing an average of about seven soundings per day in each 5° × 5° latitude box (compared to about one sounding per day in each per 5° × 5° latitude box for COSMIC-1). COSMIC-2 will use an advanced receiver known as GPS, GALILEO, and GLONASS (TriG) Global Navigation Satellite System (GNSS)-RO Receiver System (TGRS) developed by the Jet Propulsion Laboratory and a digitally beam-steered antenna. Two limb-viewing radio occultation antennas provide more than 4000 daily profiles of the neutral atmosphere (e.g. bending angle, refractivity and temperature) from typically 60 km to 1 km above the Earth's surface. The secondary payloads are the Ion Velocity Meter (IVM) and tri-band Radio Frequency Beacon (RFB). The UCAR data processing centre receives level-0 data from a set of downlink stations and processes them into higher level weather and space weather products in near real-time and post-processing modes. Products are transferred in near real-time to NOAA, NSPO, and operational weather centres worldwide. These improvements, though limited to the tropics and subtropics, will increase the value of RO observations for weather, climate and space weather research and especially tropical cyclone forecasting (Ho *et al.,* 2020; Weiss and Xia-Serafino, 2020).

The MetOp-SG mission (second generation) is a follow-up mission on the current MetOP (first generation) series of EUMETSAT. The first generation MetOp satellites are expected to ceaselessly provide high quality data for medium- and long-term meteorology and climate research until at least 2020, after which MetOp-SG becomes fully operational in 2021 and will have an overall lifetime of 21years. The second generation MetOp and GRACE-FO missions will come with improved GNSS receiver capable of tracking GPS and GALILEO satellites to double the number of occultation measurements. The recent and follow-on missions for the different RO missions will provide a revolutionary increase in the number of atmospheric and ionospheric observations over Nigeria and the entire globe, which will greatly benefit the research and operational communities, and would complement information provided by satellite radiances coupled with the fact that they can be used without bias corrections at very good vertical and horizontal resolutions.

4.0 Conclusions

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 different observing systems (radiosonde, 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. Even though, the Space-based instruments offer even broader (hypothetically global) coverage than national or regional ground-based networks at the moment, it is likely to become more useful for climate monitoring as the time series lengthens. Certainly, climatology will benefit significantly from the high accuracy, high-resolution and consistent information to be obtained from future missions as the number of RO events will increase over Nigeria. The importance of applying the GNSS RO meteorological technique in Nigeria will be never underestimated since Nigeria has large landmass (with limited weather observation stations), and large areas surrounded by ocean. As a final conclusion, the need to better integrate climate variables from GNSS atmospheric sounding techniques and other climate modelling data is encouraged. Also, better synergy among the different GNSS network operators, the IGS, world meteorological organization, global geodetic observing system and world climate research programme should be the next strategic step for Nigeria and Africa at large to optimally benefit from the offer of the GNSS atmospheric sounding techniques, this must however, be supported with complex infrastructure to provide and access rapid data.

Acknowledgement

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