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Tropopause Height Variabilities Derived from COSMIC GNSS Radio Occultation Observations over Nigeria

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ABSTRACT

This paper investigates the use of GNSS radio Occultation (RO) technique for tropopause height estimation over Nigeria. The changes or variations in the tropopause height is/are key indicators to anthropogenic climate change in the different region of the world. In this study, RO data from the Formosat-3/COSMIC (Formosa Satellite Mission 3/Constellation Observing System for Meteorology, Ionosphere, and Climate) mission for the period of 2012-2016 were used to probe the tropopause height over Nigeria. Firstly, the atmospheric profiles from the COSMIC mission were checked with ground in-situ observations (radiosonde) at two different epochs and good agreement was established between the two observing systems. The COSMIC mission is able to map the variations in solar illumination as represented in the tropopause height variation over the Nigerian region. The tropopause height varies between 15 and 18km across the different seasons and a typical range of difference between -0.235 to 3.125km was recorded between the COSMIC RO and radiosonde observations. In view of the great potential that the COMIC RO has demonstrated, the study recommends for further exploration of the troposphere utilizing datasets from recent and expected follow-on missions for the different RO missions.

1. INTRODUCTION

The Global Navigation Satellite System (GNSS) Radio Occultation (RO) technique is an innovative approach for probing the Earth's atmosphere and ionosphere using GNSS receivers on-board Low Earth Orbit (LEO) satellites (see, Kursinski et al. 1995).

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 for monitoring global temperatures, pressures, and moisture distributions.

The GNSS RO has been invaluable for many aspects of atmospheric and climate-related studies that rely on high-resolution atmospheric observations (see, Kuleshov et al. 2016). Studies have demonstrated the potential of GNSS RO profiles for characterizing troposphere structures and changes (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).

One atmospheric parameter that is important to monitor with GNSS RO is the height of tropopause. The tropopause is the region between troposphere and stratosphere. The troposphere is the layer of the atmosphere closest to the earth´s surface, which extends to about 18 km above sea level. Between the troposphere and the stratosphere, there is a middle layer called the tropopause. The tropopause plays a key role in the upper troposphere and lower stratosphere (UTLS) by affecting chemical tracers exchange. Changes in height of the global or regional tropopause can be an indicator of anthropogenic climate change (Santer et al. 2003).

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 (see, i.e., Soden and Lanzante, 1996; 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. Thus, there is the need to explore potentials of other observing systems with better spatial resolution of which the GNSS RO technique is a topmost contender in this regard.

In this study we present preliminary discussions on the structure of the tropopause over Nigeria as derived from GNSS RO observations from 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.

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2. METHOD

To discuss the structure of the tropopause over Nigeria from COSMIC GNSS RO observation, we first validated the quality of atmospheric profiles from the COSMIC mission using available Radiosonde data. Thereafter the estimated tropopause height was also validated with the same radiosonde data.

Records from the Integrated Global Radiosonde Archive (IGRA, www.ncdc.noaa.gov) show very low data record for the region of Nigeria. Fig. 1 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. 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 do not have data record is at least the last 25 years.

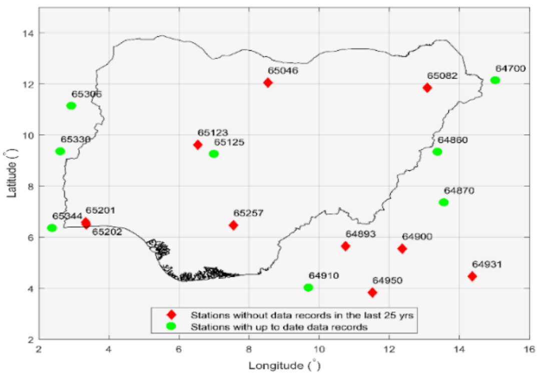

Figure 1. Distribution of Radiosonde Stations (with WMO Id) around the Nigerian Region based on Records from the IGRA, stations with up-to-date data records are marked in green diamond symbol

2.1. Evaluating Atmospheric Profiles from COSMIC GNSS RO

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, https://cdaac-www.cosmic.ucar.edu/cdaac/products.html). 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.

To 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 presented in Table 1. 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.

Table 1. *COSMIC RO event near radiosonde launch site (WMO No: 64700)*

Date	Long (∘)	Lat (∘)	COSMIC RO Events
		Epoch 1	
11 Jan 2012	14.015	12.978	C001.2012.011.14.13.G10
15 Feb 2012	14.665	13.061	C006.2012.046.14.44.G01
28 Jun 2012	14.115	12.059	C002.2012.180.02.39.G08
4 Jul 2012	14.619	13.787	C002.2012.186.12.24.G14
03 Oct 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 Jun 2016	15.168	13.836	C002.2016.182.19.45.G09
9 Jul 2016	15.068	13.943	C001.2016.191.11.00.G15
11 Jul 2016	14.889	11.830	C001.2016.193.19.08.G28
26 Jul 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.

2.2. The Estimation of Tropopause Height from COSMIC GNSS RO Observations

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;

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

In the equation (1), 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 2012-2016 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).

To 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) (see 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.

To further 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.

3. RESULTS AND DISCUSSION

3.1. Accuracy of Atmospheric Profiles from COSMIC

The Figs. 2 and 3 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).

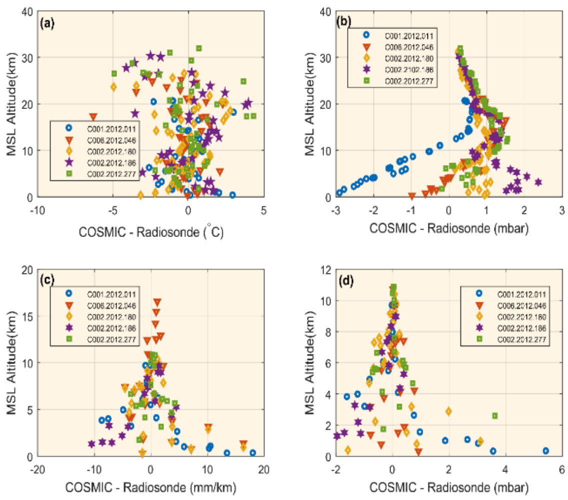

Figure 2. Shows the differences between a) temperature, b) pressure, c) refractivity, and d) water vapour pressure from FORMOSAT-3/COSMIC RO and radiosonde against the altitudes in 2012

From Figs. 2 and 3, 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 indicated 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 Figs. 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 +2.98 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 Figs. 2&3 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.

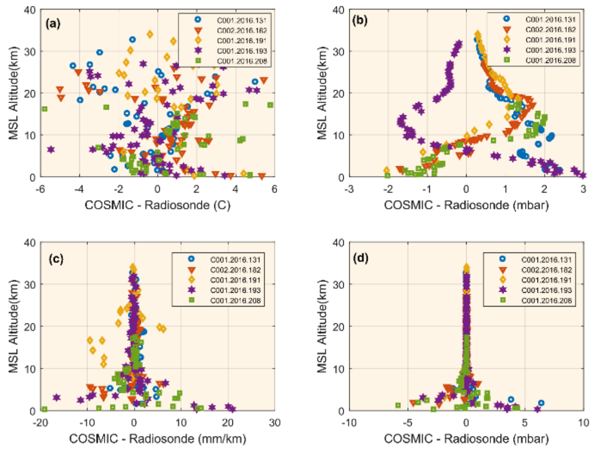

Figure 3. Shows the differences between a) temperature, b) pressure, c) refractivity, and d) water vapour pressure from FORMOSAT-3/COSMIC RO and radiosonde against the altitudes in 2016

The Fig. 4 depicts the distribution of the combined differences between the two epochs of 2012 and 2016 for the COSMIC and radiosondes observations. 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. Fig.4 is also able to reveal that pressure value is higher from COSMIC for most of the height profiles. It can be seen in Fig.4 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.

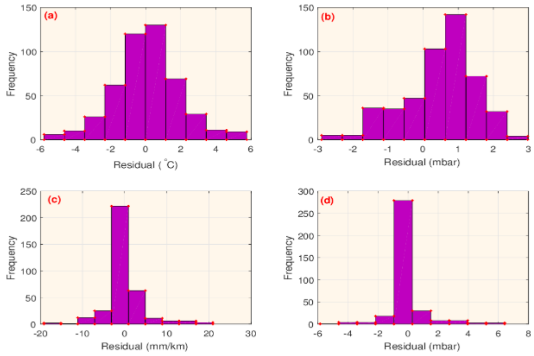

Figure 4. Frequency plot of residuals of between COSMIC and radiosonde atmospheric Profiles, a) is the temperature, b) pressure, c) refractivity , and d) water vapour profiles

3.2. Results of Tropopause Height from COSMIC and ERA-Interim

The Fig. (5) 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 Fig. (5), 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.

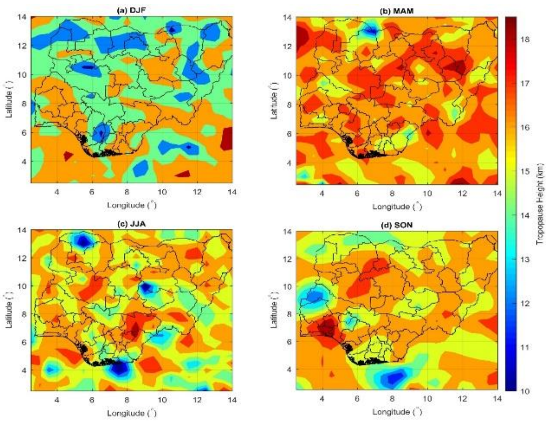

Figure 5. Seasonal mean tropopause height, a) DJF, b) MAM, c) JJA, c) SON derived from COSMIC for the period of 2012-2016 over the Nigerian region

The Fig.6 presents the seasonal estimates of the tropopause height over the Nigerian region from ERA-Interim dataset for the period of 2012-2016.

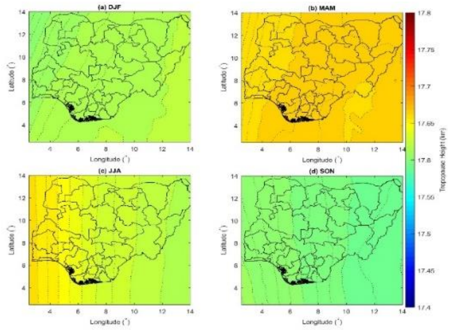

Figure 6. Seasonal mean tropopause height, a) DJF, b) MAM, c) JJA, d) SON derived from ECMWF for the period of 2012-2016 over the Nigerian region

A comparison of the seasonal pattern of GNSS RO and Era-Interim from Figs. ((5) and (6)) 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.

3.3. Accuracy of Tropopause Height from COSMIC

The summary of the result is presented in Table 2 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 2. Difference in estimated tropopause height from COSMIC and radiosonde observations

COSMIC RO Events & (Date)	Tropopause height (km)		
	COSMIC	Radiosonde	Difference
EPOCH 1			
C001.2012.011.14.13.G10 (11 January 2012)	17.550	14.425	3.125
C006.2012.046.14.44.G01 (15 February 2012)	16.894	15.405	1.489
C002.2012.180.02.39.G08 (28 June 2012)	15.650	16.165	-0.515
C002.2012.186.12.24.G14 (4 July 2012)	15.850	16.085	-0.235
C002.2012.277.08.55.G15 (03 October 2012)	17.050	15.745	1.305
EPOCH 2			
C001.2016.131.07.58.G15 (10 May 2016)	14.850	16.825	-1.975
C002.2016.182.19.45.G09 (30 June 2016)	17.050	10.485	6.565
C001.2016.191.11.00.G15 (9 July 2016)	16.750	16.585	0.165
C001.2016.193.19.08.G28 (11 July 2016)	15.150	14.885	0.265
C001.2016.208.18.50.G32 (26 July 2016)	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 give a better understanding of the transition region between the troposphere and stratosphere over the Nigerian region.

4. CONCLUSION

The paper presents the results of preliminary probes into the quality of atmospheric profiles from COSMIC GNSS RO and their consequential impact on the understanding of the tropopause height variability in the Nigerian region. Atmospheric profiles (temperature, refractivity, pressure, water vapour pressure) from COSMIC GNSS RO provided very high quality results from comparison with radiosonde observations. The GNSS RO technique is in no doubt capable of providing superior (vertical, horizontal and temporal) resolutions for atmospheric observations as compared to the radiosonde. The GNSS RO technique is able to map the variations in solar illumination as represented in the tropopause height variation over the Nigerian region. The tropopause height had some evidence of seasonal variability with value ranges of 15 to 17km. Even though, the Space-based instruments offer even broader (hypothetically global) coverage than national or regional ground-based networks now, 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.

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