(Online First)A study of temperature profiles and trends as revealed by COSMIC RO technique and balloon –borne radiosonde instrument

V. Naveen Kumar[1], M. Purnachandra Rao[2], G. Anil Kumar[3], K. Samatha[2], P. S. Brahmanandam[4]

[1] Dept. of Physics, Gudlavalleru Engineering College, Gudlavalleru, Andhra Pradesh, India

[2] Dept. of Physics, Andhra University, Visakhapatnam, Andhra Pradesh, India.

[3] School of Renewable Energy & Environment, JNTUK, Kakinada, Andhra Pradesh, India

[4] Dept. of Basic Science, Shri Vishnu Engineering College for Women, Bhimavaram, Andhra Pradesh, India.

[*] Corresponding author: dranandpotula@svecw.edu.in (Dr. P S Brahmanandam)

Abstract: This research presents atmospheric temperature profiles and trends retrieved using COSMIC RO technique and balloon-borne radiosonde instrument in 2007 and a few cases during 2017. By effectively using 'wet' temperature product available at COSMIC Data Analysis and Archive Center (CDAAC) website, an analysis has been made to present temperature profiles and trends at various regions including, Indian, Taiwan and Japan. A one-to-one correspondence is, clearly, seen between temperature profiles retrieved with COSMIC RO and radiosonde instrument. But, few and dominant differences in temperature profiles are found below at an altitude of ~5 km and above around tropopause (~16-17 km). The dominant differences found at below ~5km could be due to the inhomogeneous distribution of humidity present, generally, at the tropical regions, whereas above the tropopause altitudes, differences might be due to the ionospheric residual correction as reported by other researchers. Further, temperature monthly trends at various regions show distinct characteristics including, a sharp temperature inversion up to tropopause altitude. In addition, it is also observed maximum temperatures (peaks) during the northern summer seasons (May, June, July, and August) and minimum temperatures (troughs) during the northern winter seasons (November, December, January, and February) near to the surface of the Earth. Interestingly, although it is generally observed that the tropopause altitude is located at ~ 16-17 km at various regions, a keen observation reveals that distinct seasonal and latitudinal variations can be witnessed. With this case study, it may be concluded that the COSMIC RO technique is able to provide very accurate measurement, which reiterates its importance as a powerful tool to explore the Earth's atmosphere on the local and global scale.

Keywords: Temperature profiles; Tropopause; COSMIC RO technique; Radiosonde Instrument; Northern winter and summer seasons

1. Introduction

In order to measure climate change accurately, the long-term, global and stable observations of the vertical composition of atmospheric temperature (vertical profile) trends are very much essential[1]. However, it is not an easy task to construct a consistent temperature record using measurements from different instruments where the characteristics of the instrument may be changed due to its changing environment. For example, due to the changing instruments, observation practices, and limited spatial coverage, especially over the oceans, it is very difficult to use temperature measurements from radiosondes for climate studies. Measurements from satellite instruments provide continuous observations with a more complete spatial and temporal coverage than balloon-borne instruments (radiosondes and rawinsondes). Nevertheless, even with absolute calibration against known radiant energy

doi: 10.18063/som.v3i3.780

targets before launch, the characteristics of the satellite instrument can still change in response to the extreme environment in space. Due to changing plat-forms, diurnal cycle sampling and orbital decay, inter-satellite offsets are apparent among similar instruments onboard different satellite missions. It is critical to have accurate, consistent, stable, and well calibrated observations from different satellite missions to improve climate change monitoring.

Since 1978, the National Oceanic and Atmospheric Administration (NOAA) has equipped nine polar satellites (from NOAA6 to NOAA14) with Microwave Sounding Unit (MSU) instruments[2]. MSU, which has four channels with center frequencies in the 50 to 60 GHz oxygen band, can provide atmospheric temperature information near the surface, in the mid troposphere, upper-troposphere, and stratosphere, respectively, according to its weighting functions. Because MSU measurements are not affected by non-precipitating clouds, MSU measurements provide a very useful atmospheric layered temperature record under nearly all weather conditions[3]. Starting in 1988, MSU (onboard NOAA14) is operating in parallel with Advanced Microwave Sounding Unit (AMSU). AMSU is on- board NOAA K, L, and M series and contains more channels than MSU with some of the channels having similar frequencies to that of MSU. Because of their obvious advantage in terms of global coverage and long-term observations over the past 30 years, MSU and AMSU data have been used widely for atmospheric temperature trend detection[4–14]. However, even with continuous atmospheric-layered temperature observations from combined AMSU and MSU data, inter-satellite biases among different AMSU/MSU datasets are still obvious, due to changing platforms, the effect of on-orbit heating and cooling of satellite components, and orbit drift errors[15]. This makes the utilization of AMSU/MSU measurements for climate change detection a great challenge. Therefore, it is important to have an independent dataset, with high accuracy and long-term stability, as a climate benchmark with which to calibrate AMSU/MSU datasets for the generation of long-term coherent atmospheric temperature records.

GPS radio occultation (RO) is the first technique that can provide all-weather, high vertical resolution (from ~60 m near the surface to ~1.5 km at 40 km) refractivity profiles[16–18]. The fundamental observable of GPS RO is a precise timing measurement that is referenced to ultra-stable atomic clocks on the surface of the Earth. Since GPS RO data are not affected by weather conditions, consequently, these databases are ideally suited for use as a climate benchmark data type[16–18]. This was demonstrated by comparing the collocated GPS RO data obtained between Challenging Minisatellite Payload (CHAMP)[19] and Satélite de Aplicaciones Científicas-C (SAC-C), which showed that the precision of the averaged GPS RO profiles is about 0.1 K between 10 and 20 km[20]. The precision of 0.1 K in the mean makes GPS RO soundings ideally suited for detecting subtle climate trends. Kuo *et al*.[21] have shown that the accuracy of GPS RO data is comparable to or better than that of radiosondes. Being an active sensor, the GPS RO measurements are not contaminated by persistent clouds, precipitation, and underlying surface conditions, and therefore, are ideally suited for atmospheric climate temperature trend detection[22–23]. By using 49 months of high precision GPS RO data from CHAMP, Ho *et al*.[1] were able to characterize the differences of the monthly mean AMSU/MSU temperatures of the lower stratosphere (TLS) between the Remote Sensing Systems (RSS) Inc.[24] and University of Alabama in Huntsville (UAH)[25] groups where different data merging procedures and different satellite measurements are used as references. However, because CHAMP has only one GPS receiver, it takes more than three months to complete full diurnal coverage once over a region in the low and middle latitudes.

Recently, a series of six micro satellites namely, FORMOSAT-3/Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission (denoted as COSMIC hereafter) was successfully launched in April 2006[26]. After the satellites were deployed to operational orbits, ~2,500 GPS RO soundings have been available over the globe every 24 hours (**Figure 1**). With very high vertical resolution and accuracy, and about an order of magnitude of more soundings than previously available, with uniformly distributed data in time and space, the COSMIC RO technique presents a unique opportunity to present global trends of various atmospheric (temperature, humidity and water vapor pressure) and ionospheric parameters (electron densities, peak height of the F_2-layer and critical frequency of the F_2-layer) with unprecedented vertical and horizontal resolutions and several interesting studies have already reported using COSMIC-retrieved lower atmospheric and ionospheric parameters[26–30].

The objective of this study is to present temperature profiles and trends using the COSMIC RO-retrieved and radiosonde instrument at three different regions including, Indian, Taiwan and Japan during in 2007. Here, the year

2007 represents a year where one would expect a good number of occultations points of around ~2500/day from the COSMIC constellation around the world. In these circumstances, it is very much essential to verify temperatures profiles retrieved using the COSMIC RO technique with a well-known remote sensing instrument and this study presents such validation cases in 2007. The organization of this paper is as follows: In section 1, we present the introduction and the motivations to carry-out this research work. Section 2 presents a detailed data analysis procedure and methodology. Section 3 presents the observational results and associated discussion that supports the former. The conclusions are carefully listed in section 4, which follows acknowledgments and references.

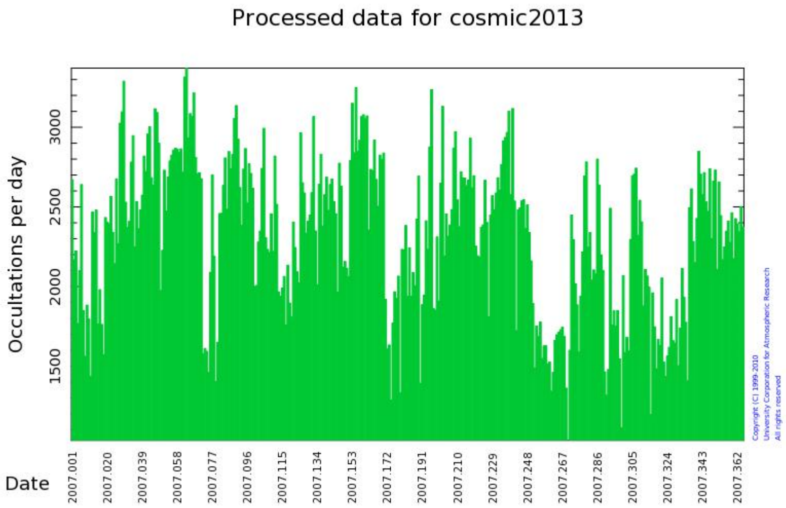

Figure 1. Global occultations made by the COSMIC satellites in 2007, which is retrieved from http://cdaac-www.cosmic.ucar.edu/cdaac/DBif/cdaac_highlevel.cgi

2. Data and Methodology

We have collected 'wet' temperature product (i.e., "wetPrf") available at the COSMIC Data Analysis and Archive Center (CDAAC) website in 2007 and the co-located radiosonde data have been archived from the atmospheric soundings website of Wyoming University, Wyoming, USA (http://weather.uwyo.edu/upperair/sounding.html). As far as the measurement mode of radiosonde is concerned, at the ground surface a highly directional radio direction finding antenna is used to obtain the wind speed and direction at various levels in the atmosphere by tracking the radiosonde and determining the azimuth and elevation angles. There are two important aspects that we have considered while doing the present validation study. The vertical resolution of COSMIC RO- retrieved temperatures is 100 meters[26] and such resolutions cannot be possible with radiosonde instrument. In order to achieve similar resolution for the co-located radiosonde measurements, we use linear interpolation technique so that similar trends can also be expected. Secondly, the horizontal distance between the radiosonde station and occultation event is within 120 km (spatial resolution) and the time window is one hour (temporal resolution).

3. Observations and discussion

3.1 Comparisons of temperature profiles during 2007

Figure 2 shows typical comparisons of temperature profiles over Taiwan (Lat. 26.07^{o} N, Long. 119.27^{o} E) region measured by the balloon-borne radiosonde and COSMIC RO technique and this figure also shows the tropopause altitude with an open circle. The day number, year, geographical latitude and geographical longitude are provided at the top of the figure along with tropopause altitude information and the similar procedure will be adopted throughout this research paper. It is obvious that temperature profiles measured by radiosonde instrument and COSMIC RO technique show a great correspondence with each other from upper troposphere (~5km) to till around 22 km. Nevertheless, no such great correspondence is found at the lower altitudes (between 0 and 6 km) as well at the upper altitudes (between 22 and 30 km). In general, due to the presence of inhomogeneous distribution of variable humidity at the tropical latitudes, high-dynamics[31] will oftentimes present at lower tropospheric altitudes that would create retrieval errors in temperature profiles[32,33]. On the other hand, the differences at upper altitudes might be due to ionospheric residual corrections.

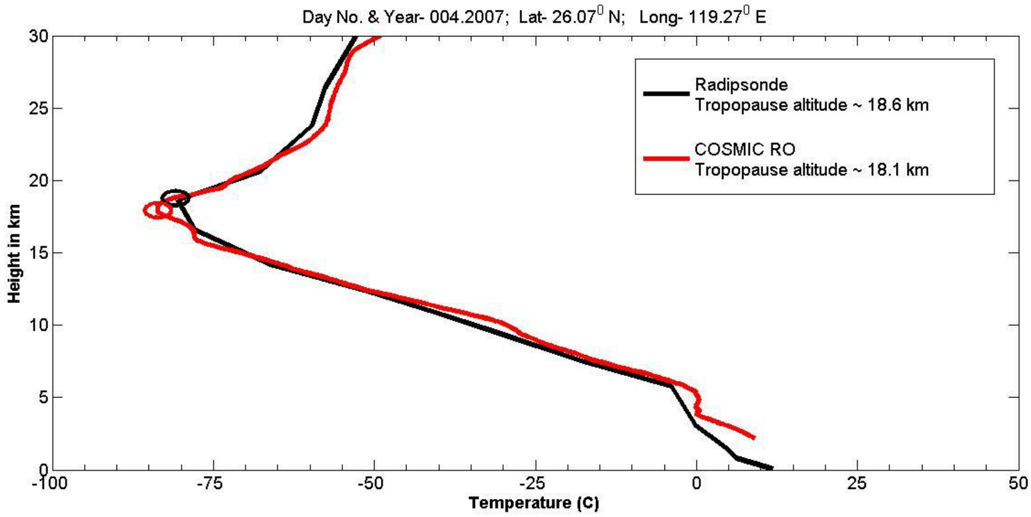

Figure 2. Comparison of temperature profiles measured using radiosonde instrument and COSMIC RO technique over Taiwan region

Figure 3 shows typical comparisons of temperature profiles over Taiwan (Latitude 25.82°N, Longitude 131.22°E) region measured by the balloon-borne radiosonde and COSMIC RO technique, which almost shows similar trends as we reported while discussing the trends of **Figure 2.** However, there is a slight difference in the tropopause altitudes between Taiwan and Japan regions. In fact, lower altitudes can be noticed at the Japanese region. This slight difference can generally be expected based on the fact that the tropopause at the transition regions between tropical and the extra-tropical regions could be due to the combined effects of troposphere and stratosphere[34].

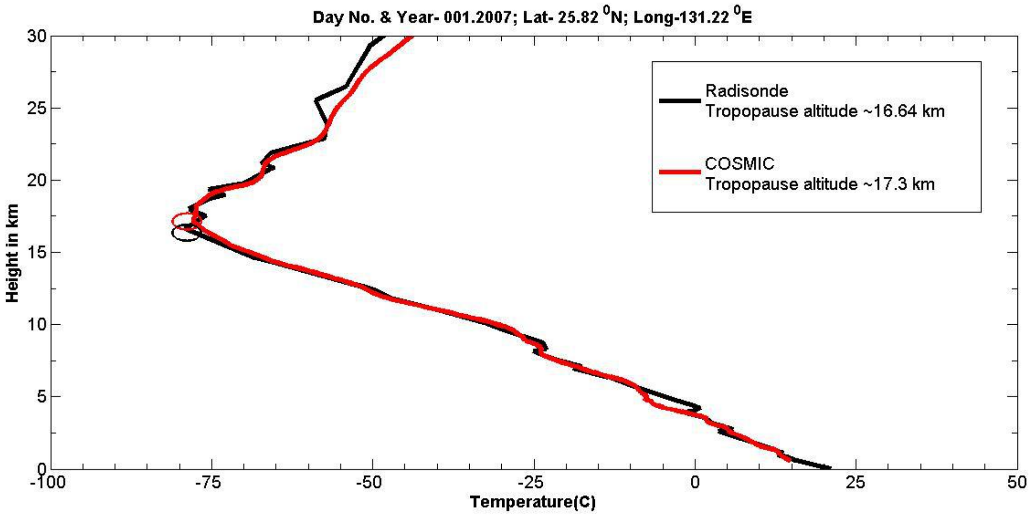

Figure 3. Comparison of temperature profiles measured using radiosonde instrument and COSMIC RO technique over Japanese region

Figure 4 shows typical comparisons of temperature profiles over Indian (Latitude 13.65° N, Longitude 81.46°E) region measured by the balloon-borne radiosonde and COSMIC RO technique, which almost shows the similar trends that we reported while discussing the trends of **Figure 2** and 3, respectively. However, almost a near altitudinal trend for tropopause in the similar lines with Taiwan region can be expected at the Indian region, since both these regions fall under tropical regions.

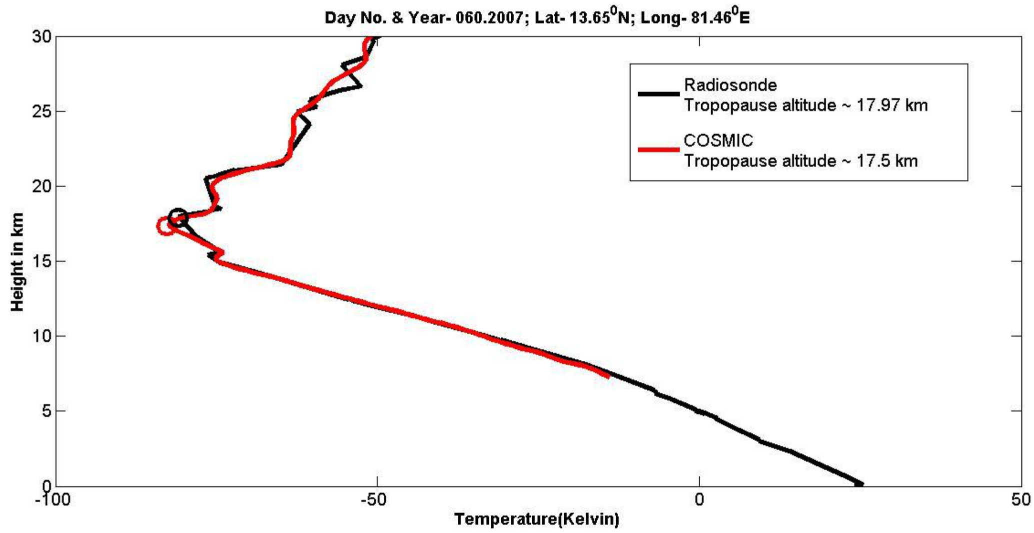

Figure 4. Comparison of temperature profiles measured using radiosonde instrument and COSMIC RO technique over Indian region

3.2 Comparison of temperature trends using radiosonde instrument

The monthly variations temperature trends at Taiwan region is shown in **Figure 5.** From the Figure 5, one can notice temperatures greater than 20^{o}C from May 2007 to October 2007 and again from May 2008 to October 2008 up to around 5 km height (indicated by dark red color in legend), which represent summer seasons for the northern hemisphere. In addition, a dip in temperatures can also be easily seen from the mid January 2007 to mid December 2007 and from February 2008 to December 2008 (winter season in northern hemisphere). Further, a gradual decrease in temperatures is seen with the progress of altitude (temperature inversion) with an extremely minimum temperature (~ -70^0 C) at around 16-18 km altitude and this maximum dip in temperature depicts the tropopause, a thermal boundary that often uses to distinguish the stratosphere and troposphere regions of the Earth's atmosphere that plays a significant role in stratosphere-troposphere coupling and exchange[34].

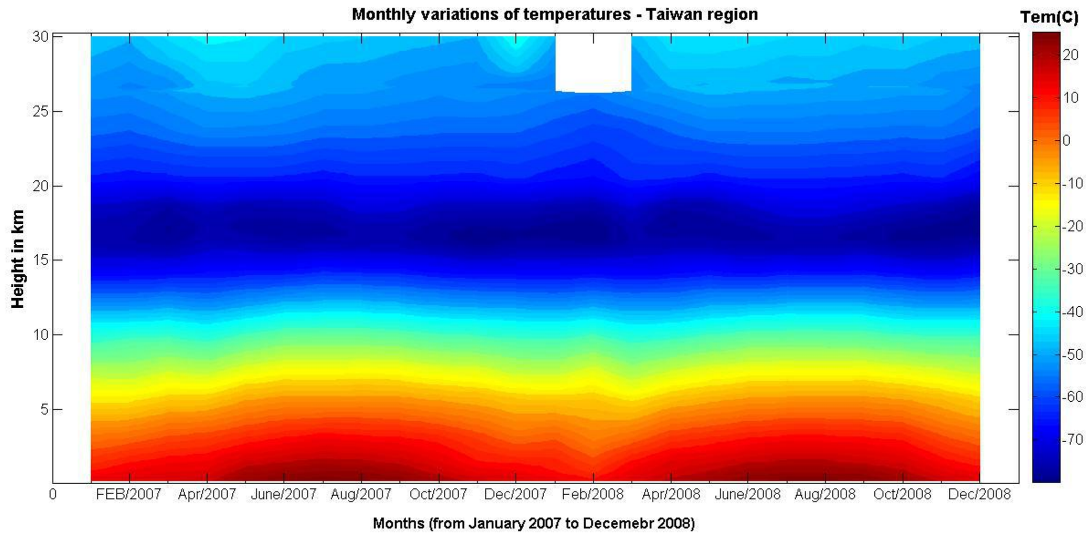

Figure 5. Monthly (January 2007 -December 2008) variations of temperatures over Taiwan region

It is obvious from **Figure 6** that one can notice temperatures greater than 20^{o}C from May 2007 to October 2007 and from May 2008 to October 2008 up to 5 km height and a temperature dip (around 20^{o}C) from November 2007 to March 2008 and such a similar dip is going to be observed from again from mid December 2007 and from March 2008 to December 2008 up to 2km height. As expected, a gradual decrease of temperatures above 5 km altitude is generally observed with a dip at around 15-16 km. It may be worth mentioning here that tropopause at tropical latitudes shows distinct seasonal variations and, in general, northern hemisphere winter season would show higher magnitudes when compared to the trends that observed during the northern hemisphere summer season[35].

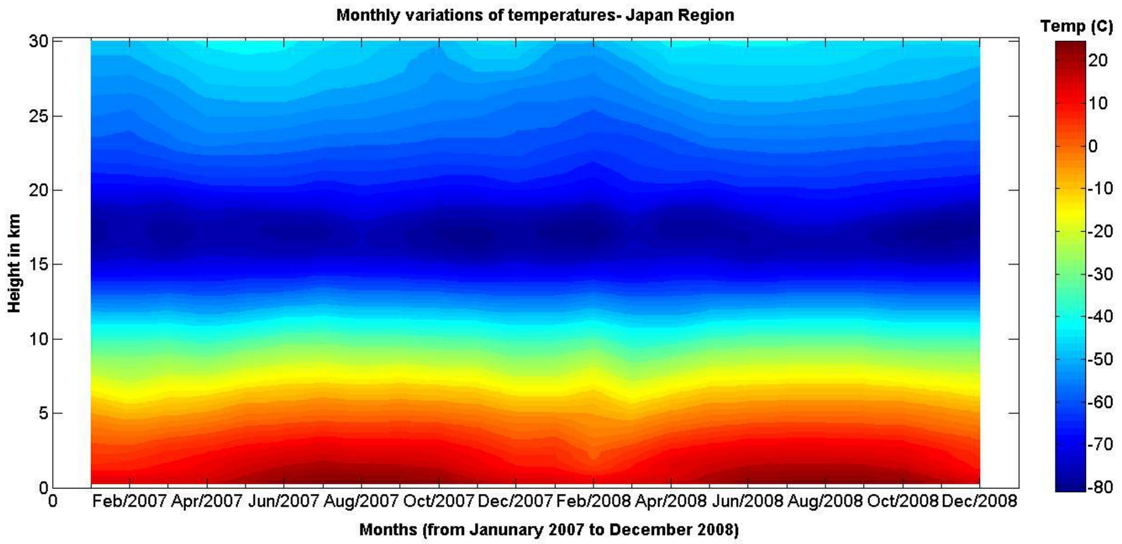

Figure 6. Monthly (January 2007 -December 2008) variations of temperatures over Japan region

The monthly (from January 2007 to December 2008) temperature trends over Indian region are presented in **Figure 7.** It is, easily, seen from Figure 7 that greater than 20^{o}C temperatures can be observed from May 2007 to October 2007 and, again, from May 2008 to October 2008 up to ~5 km height, with a dip in temperature trends can be seen during the northern summer seasons. In addition, a distinctive temperature inversion with respect to altitude is a dominant observational phenomenon and an extreme minimum values observed at around 16-18 km (tropopause).

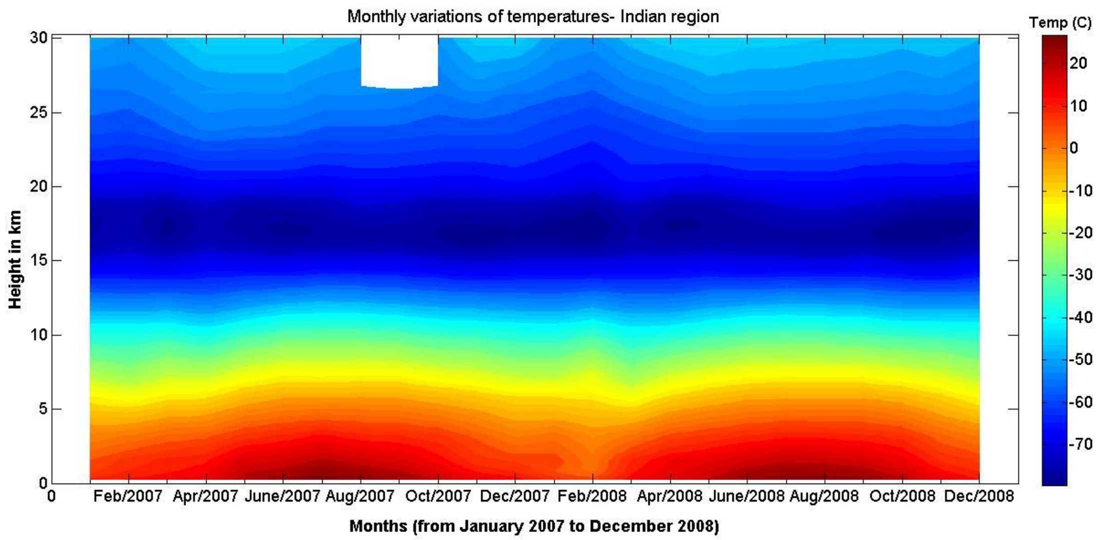

Figure 7. Monthly (January 2007 -December 2008) variations of temperatures over Indian region

Since a global snapshot of temperature trends is only possible with COSMIC RO technique, we present global temperature trends during various months including, March, April and May 2007. **Figure 8**a, 8b and 8c show temperature trends over the equator (between 5^{0} S and 5^{0} N), in which the longitudinal versus height variations of temperatures are shown. It is quite obvious from these figures that a distinctive altitudinal variation can be seen with a tropopause at around 16- 17 km altitude. More or less, equal temperature trend are seen during these months.

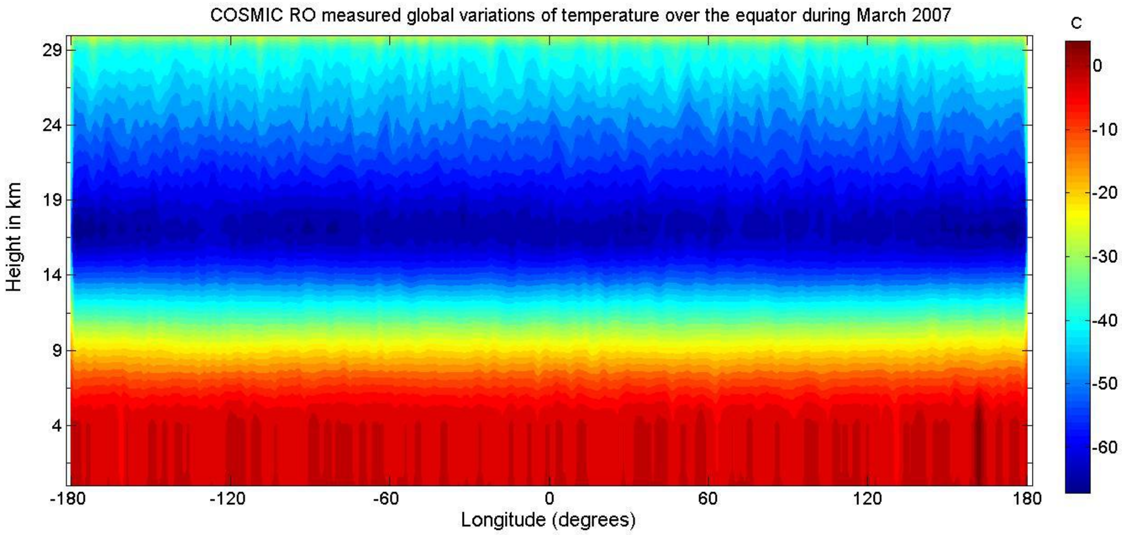

Figure 8a. Global variations of COSMIC RO measured temperature over the equator averaged between 5^0S-5^0N in March 2007

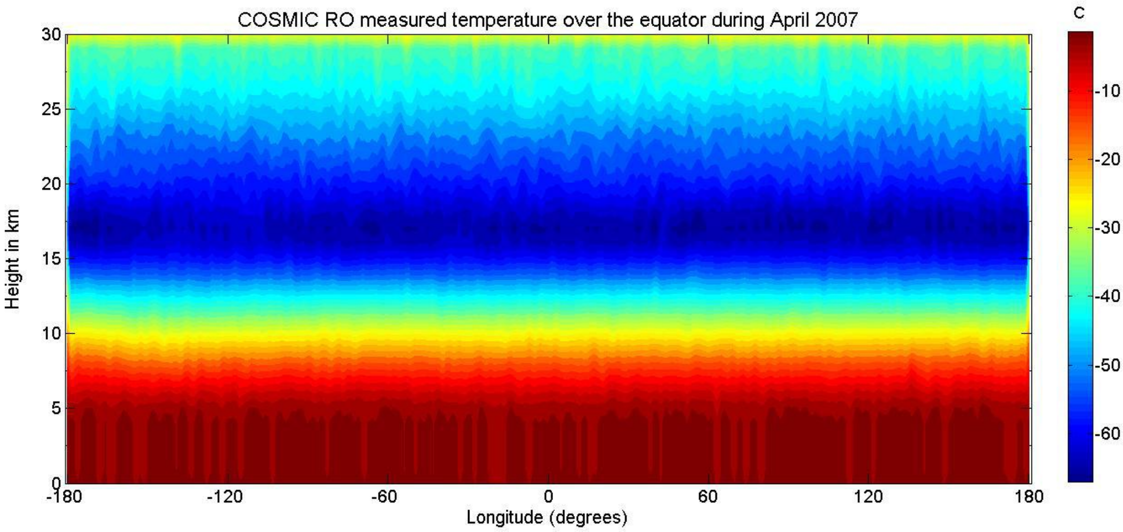

Figure 8b. Global variations of COSMIC RO measured temperature over the equator averaged between 5^0S-5^0N in April 2007

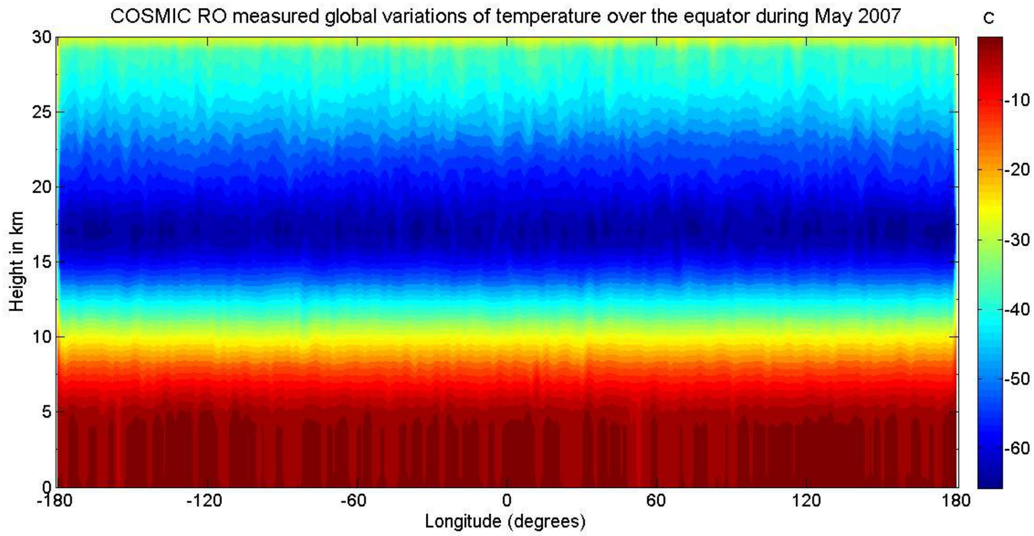

Figure 8c. Global variations of COSMIC RO measured temperature over the equator averaged between 5^0S-5^0N in May 2007.

3.3 Comparisons of temperature profiles during 2017

In order to verify the temperature profiles during a year when less number of occultations is available (less than ~1,000/day around the world)[36], it is important to know the accuracy of the COSMIC RO technique. In this regard, we present a few comparative studies at various locations in 2017. At outset, **Figure 9** shows the number of occultations possible with six COSMIC micro satellites in 2017. It is quite obvious from this figure that though the early phase of 2017 shows occultations near to 800/day, too meager occultations are noticed, particularly, between April and September.

It is worth to mentioning here that the reduction in the number of radio occultation's per day may be attributed either due to residual contamination of the satellite signal by high water vapor concentration, onboard sensor degradation, aging of satellites and frequent shutdowns or spatial and temporal data resolution enhancements adopted at the CDAAC centre which are critical to assess the quality of satellite based retrieval data system.

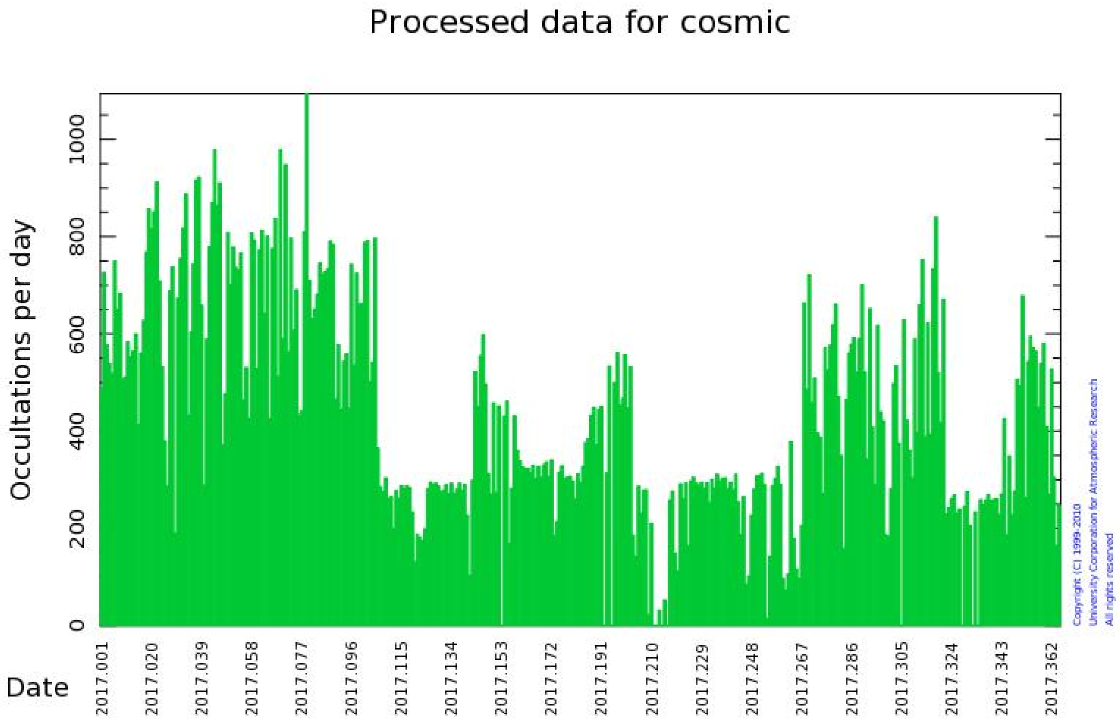

Figure 9. Global occultations made by the COSMIC satellites in 2017, which is retrieved from http://cdaac-www.cosmic.ucar.edu/cdaac/DBif/cdaac_highlevel.cgi

Figure 10 presents a comparative study of temperature profiles measured using radiosonde instrument and COSMIC RO technique during 01 January 2017. A few differences in temperature profiles are noticed in the similar lines with the profiles observed during year 2007, particularly at lower and upper altitudes, but a drastic change is noticed at the tropopause altitude. In fact, a moderate difference in tropopause altitude and its spatial variation between radiosonde and the COSMIC RO technique measured temperatures can be seen and such moderate differences are also reported by other researchers from the Indian sector[37].

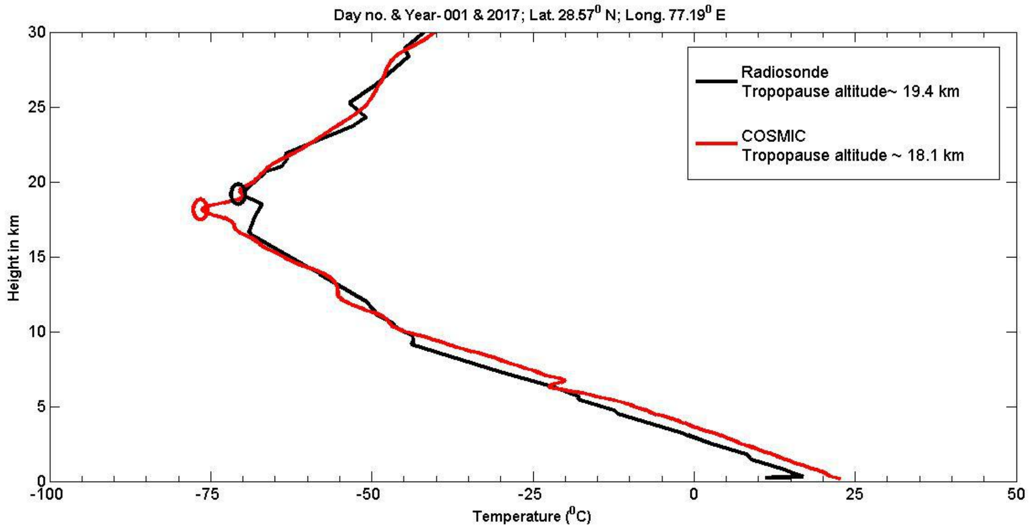

Figure 10. Comparison of temperature profiles measured using radiosonde instrument and COSMIC RO technique over Indian region

In order to further verify whether such similar differences with other temperature profiles really exist or not, we also show another comparison on 1 March 2017 in **Figure 11** along with a few more days in 2017 (not shown here). Interestingly, any significant deviations are not observed except the low-altitude and high-latitude differences that are generally observed while presenting the temperature trends during 2007. These comparisons, therefore, show that the COSMIC RO techniques is able to provide local and global temperature trends effectively even though it has completed almost twelve years (launched in April 2006).

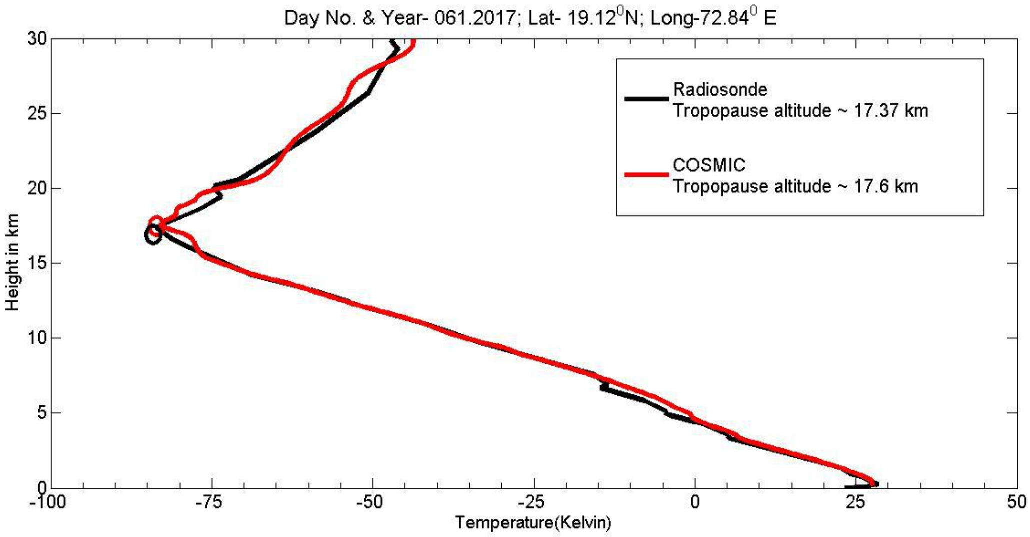

Figure 11. Comparison of temperature profiles measured using radiosonde instrument and COSMIC RO technique over Indian region

4. Conclusions

The launch of COSMIC GPS RO technique has opened new avenues to study the global atmosphere with a relatively higher resolution from the surface of the Earth to an altitude of 800 km. By effectively utilizing huge database available from the COSMIC RO satellites, an attempt is made to explore the robustness of radio occultation technique by comparative analysis. In this context, we have observed several important results that are outlined as follows:

1) Validation studies of temperature profiles at individual locations including, Taiwan, Indian and Japan between COSMIC retrieved and radiosonde measured reveal a good agreement between them in 2007, although a few

differences (below ~5 km and above tropopause ~16-17 km) are found

2) The few difference found at lower altitudes and upper altitudes could be due to the inhomogeneous distribution of humidity and ionospheric residual correction

3) Although there is a drastic reduction in the number of radio occultation's received per day in 2017 (~800/day), a similar coherence is found for temperatures observed with radiosonde and the COSMIC RO technique- measured ones.

4) It is revealed from the temperature monthly trends that a sharp temperature inversion, distinct seasonal variations i.e. maximum (minimum) magnitudes during the northern summer (northern winter) seasons.

5) In the majority of the cases (India, Taiwan and Japan regions and these come under tropical and extra-tropical regions), the tropopause is located at around 16-18 km, and

6) Typical comparisons between vertical temperature profiles derived from COSMIC GPS RO data and near-by radiosonde measurements during 2017 reveal high coherency which provides confidence in temperature profiles derived from COSMIC RO data.

Acknowledgements:

The corresponding author, Dr. P. S. Brahmanandam, greatly acknowledges the management of SVECW, Bhimavaram, India for their logistic support, without which it would not have been possible for him to carry-out this important research. Radiosonde-based data have been downloaded from the Wyoming University, Wyoming, USA website http://weather.uwyo.edu/upperair/sounding.html. We acknowledge the CDAAC for providing valuable COSMIC GPS-RO datasets at https://cdaac-www.cosmic.ucar.edu/ and https://tacc.cwb.gov.tw/cdaac/index.html.

References

1. Xu G, Yue X, Zhang W, *et al*. Assessment of atmospheric wet profiles obtained from COSMIC radio occultation observations over China. Atmosphere 2017; 8(11): 208.
2. https://www.nasa.gov/pdf/298662main_NOAA-N%20Prime%20Booklet%2012-16-08.pdf.
3. Folland CK, Thomas RK, Salinger MJ. Observed climate variability and change. Weather 2002; 57: 269-278.
4. Spencer RW, Christy JR. Precision and radiosonde validation of satellite grid point temperature anomalies, Part I: MSU channel 2. J. Climate 1992a; 5: 847–857.
5. Spencer RW, Christy JR. Precision and radiosonde validation of satellite grid point temperature anomalies, Part II: A tropospheric retrieval and trends during 1979-90. J. Climate 1992b; 5: 858–866.
6. Christy JR, Spencer RW, Lobl ES. Analysis of the merging procedure for the MSU daily temperature time series. J. Climate 1998; 5: 2016-2041.
7. Christy JR, Spencer RW, Braswell WD. MSU tropospheric temperatures: Dataset construction and radiosonde comparisons,Journal of Atmospheric and Oceanic Technology 2000; 17: 1153-1170.
8. Christy JR, Spencer RW, William BN, *et al*. Error estimates of version 5.0 of MSU–AMSU bulk atmospheric temperatures. Journal of Atmospheric and Oceanic Technology 2003; 20: 613-629.
9. Fu Q, Johanson CM. Stratospheric influences on MSU-derived tropospheric temperature trends: A direct error analysis. J. Climate 2004; 17: 4636–4640.
10. Mears CA, Schabel MC, Wentz FJ. A reanalysis of the MSU channel 2 tropospheric temperature record. J. Climate 2003; 16: 3650–3664.
11. Vinnikov KY, Grody NC. Global warming trend of mean tropospheric temperature observed by satellites. Science 2003; 302: 269–272.
12. Vinnikov KY, Grody NC, A Robock, *et al*. Temperature trends at the surface and in the troposphere. Journal of Geophysical Research 2006; 111: 1-14(D03106).
13. Grody NC, Vinnikov KY, Goldberg MD, *et al*. Calibration of multi-satellite observations for climatic studies: Microwave Sounding Unit (MSU). Journal of Geophysical Research 2004; 109: 1-12(D24104).
14. Zou CZ, Goldberg MD, Cheng Z, *et al*. Recalibration of microwave sounding unit for climate studies using simultaneous nadir overpasses. Journal of Geophysical Research 2006; 111: (D19114).
15. Karl TR, Hassol SJ, Miller CD, *et al*. Temperature trends in the lower atmosphere: Steps for understanding and reconciling differences, U.S. Climate Change Science Program and the Subcommittee on Global Change Research Synthesis and Assessment Product 1.1, 2006; 164 pp.
16. Kursinski ER, Hajj GA, Schofield JT, *et al*. Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System. Journal of Geophysical Research 1997; 102: 23429-23465.
17. Yunck TP, Liu CH, Ware R. A history of GPS sounding. Terrestrial, Atmospheric and Oceanic Science 2000; 11: 1-20.
18. Kuo YH, Wee TK, Sokolovskiy S, *et al*. Inversion and error estimation of GPS radio occultation data. Journal of

the Meteorological Society of Japan 2004; 1B: 507– 531.
19. Hajj GA, CO Ao, Iijima BA, *et al*. CHAMP and SAC-C atmospheric occultation results and intercomparisons. Journal of Geophysical Research 2004; 109: D06109.
20. Wickert J, Beyerle G, K¨onig, *et al*.GPS radio occultation with CHAMP and GRACE: A first look at a new and promising satellite configuration for global atmospheric sounding. Annales Geophysicae 2005; 23: 653–658.
21. Kuo YH, Schreiner WS, Wang J, *et al*. Comparison of GPS radio occultation soundings with radiosondes. Geophysical Research Letters 2005; 32: L05817.
22. Schrøder T, Leroy S, Stendel M, *et al*. Validating the microwave sounding unit stratospheric record using GPS occultation. Geophysical Research Letters 2003; 30(14): 1734(1-4).
23. Gavin AS, Drew TS, Ron LM, *et al*. General circulation modelling of Holocene climate variability. Quaternary Science Reviews 2004; 23: 2167–2181.
24. Gobiet UF, AK Steiner, M Borsche, *et al*. Climatological validation of stratospheric temperatures in ECMWF operational analyses with CHAMP radio occultation data. Geophysical Research Letters 2005; 32: L12806(1-5).
25. Mears CA, FJ Wentz. The effect of diurnal correction on satellite-derived lower tropospheric temperature. Science 2005; 309: 1548–1551.
26. Brahmanandam PS, YH Chu, J Liu. Observations of equatorial Kelvin wave modes in FORMOSAT-3/COSMIC GPS RO temperature profiles. Terrestrial, Atmospheric and Oceanic Sciences 2010; 21(5): 829–840.
27. Brahmanandam PS, YH Chu, KH Wu, *et al*. Vertical and longitudinal electron density structures of equatorial E- and F-regions. Annals of Geophysics 2011; 29: 81–89.
28. Brahmanandam PS, U Gouthu, JY Liu, *et al*. Global S4 index variations observed using FORMOSAT-3/COSMIC GPS RO technique during a solar minimum year. Journal of Geophysical Research 2012; 117: A09322.
29. Potula BS, YH Chu, Uma G, *et al*. A global comparative study on the ionospheric measurements between COSMIC radio occultation technique and IRI model. Journal of Geophysical Research 2011; 116: A02310.
30. Uma G, Brahmanandam PS, Chu YH. A long-term study on the deletion criterion of questionable electron density profiles caused by ionospheric irregularities – COSMIC radio occultation technique. Advances in Space Research 2016; 57: 2452-2463.
31. Ao C, Hajj GA, Meehan TK, *et al*. Rising and setting GPS occultations by use of open-loop tracking. Journal of Geophysical Research 2009; 114: D04101.
32. Rocken C, YH Kuo, W Schreiner, *et al*. COSMIC System Description, Special issue of Terrestrial, Atmospheric and Oceanic Sciences 2000; 11(1): 21-52.
33. Rieckh T, Scherllin-Pirscher B, Ladstädter F, *et al*. Characteristics of tropopause parameters as observed with GPS radio occultation. Atmospheric Measurement Techniques 2014; 7: 3947–3958.
34. Holton JR, Haynes PH, McIntyre ME, *et al*. Stratosphere-troposphere exchange. Reviews of Geophysics 1995; 33(4): 403– 439.
35. Anil Kumar G, K Vijay Kumar, G Uma, *et al*. Global trends of tropopause observed from COSMIC radio occultation technique during 2007-2012. International Journal of Scientific & Engineering Research 2014; 5(6): 1318-1328.
36. Nick LY, Fong CJ, Chang GS. Approaching the first global radio occultation operational mission using. Constellation LEO Satellites, EUMETSAT Meteorological Satellite Conference, Sopot, Poland, 2012
37. Narayana Rao D, Ratnam MV, Mehta S, *et al*. Validation of the COS MIC radio occultation data over Gadanki (13.48°N, 79.2°E): A tropical region. Terrestrial, Atmospheric and Oceanic Sciences 2009, 20, pp. 59-70.