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Validation of the COSMIC Radio Occultation Data over Gadanki (13.48 N, 79.2 E): A Tropical Region

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ABSTRACT

Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC), consisting of six Low Earth Orbit (LEO) Global Position System (GPS) receivers, on board the Formosat Satellite 3 (FORMOSAT-3) is providing dense observations of density, refractivity, temperature and water vapor profiles of the neutral atmosphere since middle of July 2006. Special radiosonde (Väisälä) campaign was conducted at Gadanki (13.48 N, 79.18 E), a tropical site in India, during July 2006 to March 2007 to validate these meteorological parameters. Co-located Nd: YAG Rayleigh lidar was also operated during the overpass of COSMIC and is utilized to validate the temperatures in the height range of 30 to 40 km. A total of 142 overpasses occurred during the above mentioned period within 300 km distance from Gadanki out of which 41 overpasses occurred within a time difference of 4 hours of radiosonde launch. In addition, 18 overpasses occurred within the time difference of 4 hours of lidar operation. A detailed comparison has been made with all these overpasses for the refractivity, temperature and water vapor obtained from COSMIC. The water vapor comparison has shown generally a good agreement with a mean difference of 5 - 10% below 6 - 7 km. Although there is a colder bias between COSMIC and radiosonde, a very good comparison in temperature is also found between 10 and 27 km with a mean difference of less than 1 K (RMS difference is only 0.64 K). There exists a large difference in temperature of about 8 K between 30 and 40 km (between COSMIC and lidar). Possible reasons for these large differences are given. There was one event that occurred just over Gadanki for which a detailed comparison has been made with special emphasis on water vapor retrievals. Sensitivity test is also done on the fractional difference in N for the event that occurred on 24 July 2006 between COSMIC (1D-var) and radiosonde and found that pressure plays a key role than temperature in determining the refractivity.

Key words: GPS RO, Water vapor, Temperature, Validation

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1. INTRODUCTION

Radio occultation soundings of the signals from the Global Positioning System Satellites (GPS) are being used to obtain vertical profiles of atmospheric temperature, pressure and water vapor for climate research and weather prediction (Kursinski et al. 1997). The GPS Radio occultation technique has emerged as a powerful tool for exploring the earth's atmosphere from ground to a height of around 40 km and also in the ionosphere after the successful launch of GPS/MET which has provided a 'proof of concept' of GPS Radio Occultation (RO) technique. Several missions such as Oersted and SAC-C (Hajj et al. 2004) followed GPS/

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MET. However, CHAMP (German mission, Wickert et al. 2001) which provided a wealth of information by not only providing profiles with good accuracy but also on long-term basis. Although this data set was utilized for operational usage, the number of profiles (200 - 250 globally distributed GPS occultations every day) was very limited to consider the changes across the globe with good spatial resolution.

Recently, Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC)/Formosa Satellite 3 (FORMOSAT-3) (Rocken et al. 2000), a Taiwan and USA joint mission, was launched on 14 April 2006 consisting of six-satellites (Schreiner et al. 2007). By taking advantage of tracking the signals in both rising and setting occultations, COSMIC is providing about 2000 (final target is around 2500 - 3000 occultations per day) occultations per day across the globe which is about 10 times larger than CHAMP observations. Additional advantage is the ability to track signals from the lowest height regions than other missions since open loop tracking is employed in COSMIC in the lowest 10 km. Although GPS RO is a well proven technique, yet detailed comparison of all its retrieved parameters with independent reliable techniques over different regions is necessary. This comparison is particularly necessary for tropical latitudes since the weather conditions of the tropical region are more diverse with large horizontal humidity gradients with complicated structures than those observed over the mid latitudes.

The radiosonde is an operational instrument since decades but it suffers from radiation error in temperature measurements (e.g., Luers and Eskridge 1998; Wang et al. 2003) and humidity measurement is very challenging especially in the upper troposphere where humidity concentrations are very low. Over India 34 radiosonde stations are operational which use IM-MK3 type sensor. The location map of these radiosonde stations is shown in Fig. 1. Statistical comparison of refractivity calculated using radiosonde data with simultaneous (within 300 km radial distance and 2 hours

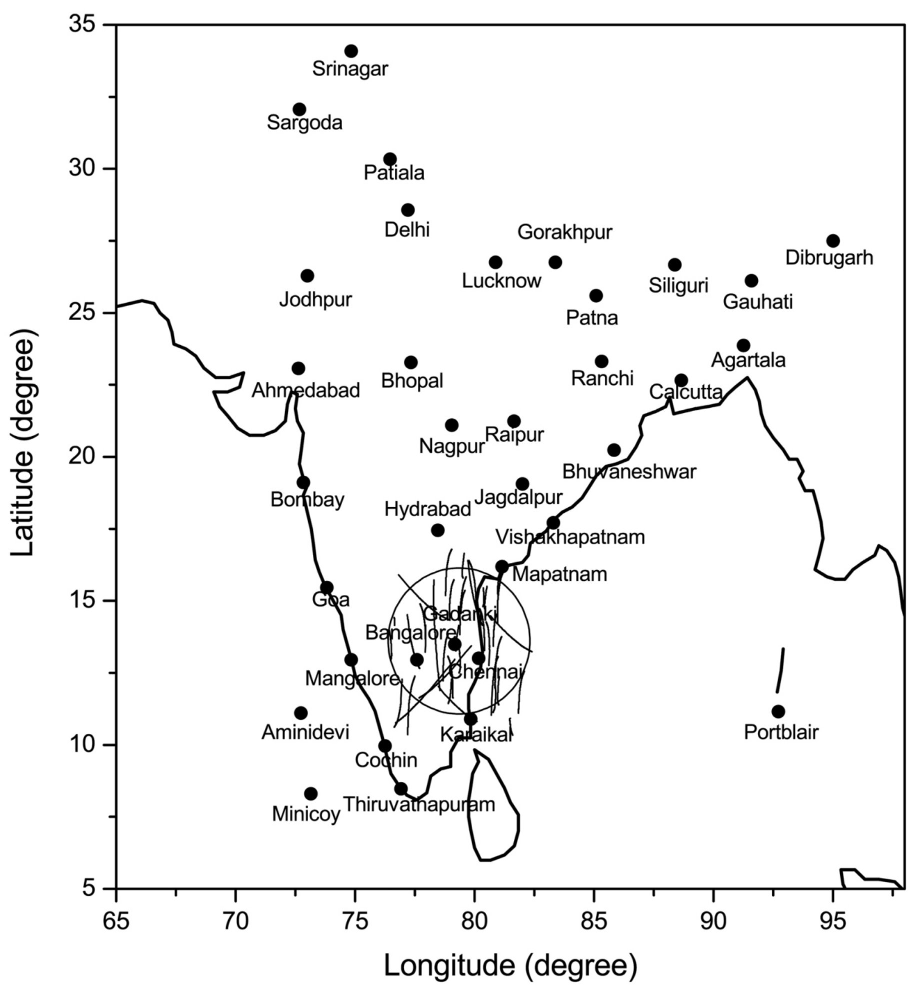

Fig. 1. Map showing the upper air stations (blue diamond dots) located in India operated by India Meteorological Department. Gadanki selected as a validation site for COSMIC RO data is shown in the filled circle. The tangent points of the occultations that occurred within 300 km distance from Gadanki are also plotted.

time difference) CHAMP observations has large fractional difference of 0.82% with standard deviation of 3.2 (Kuo et al. 2005). However, with Väisälä type sensor at other locations, it has shown mean fractional difference of only 0.18% with standard deviation of 1.3 (Kuo et al. 2005). Therefore it is necessary to validate the atmospheric profiles such as refractivity and temperature from ground based standard instruments over India (at a tropical site). Water vapor is another crucial atmospheric parameter in weather and climate. We have taken the COSMIC RO data processed and provided from Taiwan TACC data center. This data includes water vapor profile which is derived using 1-D variation method. All the parameters from COSMIC RO are validated using independent measurements from radisonde and Lidar which are specially launched/operated during overpass of COSMIC over Gadanki.

2. DATA BASE

2.1 Radiosonde (Väisälä RS-80H and RS-92 Type)

Owing to the importance of tropical latitudes and large difference between GPS RO and India Meteorological Department (IMD) routine radiosonde observations, Väisälä (RS80 and RS92) radiosondes were specially launched for validation of COSMIC RO data from Gadanki (13.48 N, 79.18 E), a tropical site in India during July 2006 to March 2007. Routinely radiosonde has been launched around 12 UT (LT = UT + 5:30 hours). Additional radiosondes were also launched whenever there is an overpass over Gadanki. The location of this site is also shown in Fig. 1 with a filled circle. The atmospheric parameters (pressure, temperature, water vapor, and horizontal winds) were determined with a height resolution of 25 - 30 m (sampled at 5 seconds intervals) from RS-80 type and 10 m (sampled at 2 seconds intervals) from RS-92. Later the entire data set has been interpolated to 100 m so as to remove outliers arising due to random motion of the balloon. Quality checks were then applied to remove outliers arising due to various reasons following Tsuda et al. (2006) to ensure high quality in the data which otherwise contaminate the entire results.

Data was collected during the day of overpass of COSMIC satellite within 3 of latitude and longitude of Gadanki (corresponding to 300 km radial distance) and a time difference of 4 hours in order to reduce the error due to temporal and spatial differences, if any. There are totally 41 such coincidences between COSMIC and GPS radiosonde launches out of which 2 launches data set were rejected from further analysis due to the radiosonde either reaching not more than 8 km or drifting for more than 500 km due to peculiar weather conditions. The 39 (22/17 in day/night) overpasses data have been utilized for a detailed comparison of refractivity, temperature and water vapor between COSMIC and GPS radiosonde. The tangent points for all the occultations that occurred within 300 km from Gadanki are also shown in Fig. 1.

2.2. COSMIC RO Data

We used post-processed GPS RO data obtained by COSMIC satellite from July 2006 to March 2007, which are processed by TAAC data center, Taiwan. This joint Taiwan-US mission consisting of six identical micro-satellites was successfully launched into near-polar orbit (inclination = 72) by a US Air Force "Minotaur" rocket from Vandenberg at 0140 UTC 15 April 2006. By employing the GPS RO technique, COSMIC provides temperature and water vapor profiles (1D-var retrival) in the troposphere and lower stratosphere. The vertical resolution of the temperature profiles ranges from 0.5 km in the lower troposphere to 1.4 km in the stratosphere. However, we have interpolated the data to 100 m. The horizontal resolution along the path is about a few hundred km. TAAC center provides about 2000 globally distributed vertical profiles of temperature and water vapor data every day over the height range of 0.1 - 40 km.

2.3 Nd: YAG Rayliegh Lidar Data

Temperature data from co-located Nd: YAG Rayleigh lidar, which provides temperature information right from 30 to 80 km, is also used to validate the temperature profile between 30 and 40 km. The Lidar has been operated on all clear sky nights and there were 18 coincidences between COSMIC overpass and Nd: YAG Rayleigh lidar observations with the above mentioned selection criteria. This lidar employs the second harmonic of Nd: YAG pulsed laser at 532 nm with an energy of about 550 mJ at a pulse repetition rate of 20 Hz and a pulse width of 7 ns. The transmitted beam has a divergence of 0 : 1 m rad, vertically. More details of this instrument and method of analysis can be had from Ratnam et al. (2002). The method of analysis for determination of temperature profile from Rayleigh scattering follows closely that given by Chanin and Hauchecorne (1984). In the height range where Mie contribution is negligible (30 - 80 km), the recorded signal intensity, corrected for the range and atmospheric transmission, is proportional to the molecular number density. Using the number density taken from an appropriate model (CIRA-86) for the height of 50 km where the signal-to-noise ratio is fairly high, the constant of proportionality is evaluated and thereby the density profile is derived. Taking the pressure at the top height (80 km) from the atmospheric model, the pressure profile is computed using the measured density profile assuming the atmosphere to be in hydrostatic equilibrium. Adopting the ideal gas law, the temperature profile is obtained using the derived density and pressure profiles. Any uncertainty in the pressure at the top of the profile would contribute to temperature uncertainty that falls rapidly with decreasing altitude. For 15% uncertainty in the pressure at the top of the height range, the temperature uncertainty would be < 2% at 15 km below the top. Complete details about the temperature retrieval and errors involved were given by Parameswaran et al. (2000). The temperature profile can be obtained with a vertical resolution of 300 m, however, we have interpolated the data to 100 m for comparison with other instruments.

3. METHODOLOGY

The basic parameter estimated using GPS RO is the phase delay from which vertical profile of Bending Angle (BA) can be retrieved. Vertical profile of Refractivity (N) can be estimated from the profile of bending angle using Abel transform. It is well known that the refractivity, which is a function of refractive index (n) gradients, depends mainly on temperature and humidity gradients in the lower atmosphere and electron density gradients in the upper atmosphere and is given by the following equation (Kursinski et al. 1997):

$$N = (n-1) \times 10^6 = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{P_w}{T^2} + 4.05 \times 10^7 \frac{n_e}{f^2} + 1.4w \qquad (1)$$

where N is refractivity, P is atmospheric pressure in hPa, T is atmospheric temperature in Kelvin, P_w is water vapor partial pressure in hPa, n_e is electron density per cubic meter, f is transmitter frequency in Hertz, and w is liquid water content in grams per cubic meter. The four refractivity terms in Eq. (1) are referred to dry, moist, ionospheric, and scattering terms. The dry and moist terms are dominant mainly below 60 and 10 km (particularly in the tropics), respectively. The ionospheric term is mainly relevant from the region above 60 km. The scattering term is due to liquid water droplets suspended in the atmosphere. The contribution of this term to the total refractivity is very small and hence can be neglected. Refraction in the ionosphere is dispersive and frequency dependent which can be separated making use of the dual frequencies being transmitted by the GPS satellites. Now the only two main contributors for the refractive index gradients are the temperature and humidity gradients in the neutral atmosphere. By assuming the atmosphere to be dry which is true roughly above 10 km in the tropics, one can estimate the temperature accurately in principle from 10 to 40 km. With prior knowledge of reasonably accurate independent temperature information, one can estimate the humidity profile in the first 10 km of the earth's atmosphere.

Among 39 occultations that occurred within 300 km distance from Gadanki and 4 hours time difference, one occultation occurred very close by to Gadanki on 24 July 2006. This event has been examined in more detail with special emphasis on water vapor comparison. The tangent point of this occultation is shown in Fig. 2a. The Väisälä radiosonde was released at 0013 UT and the COSMIC overpass was at 0345 UT. The radiosonde trajectory i.e., east-west and north-south distance of the balloon at different heights from the launch site on this day is shown in Fig. 2b. Note that at 5 km altitude, there was only 35 km horizontal separation between the radiosonde and COSMIC over-pass.

Before going to details of the results, we briefly outline the methodology adopted for estimation of water vapor from both COSMIC and GPS radiosonde. The water vapor from radiosonde is calculated using temperature and relative humidity by the following equations:

$$e_s = e_{st} 10^Z \qquad (2)$$

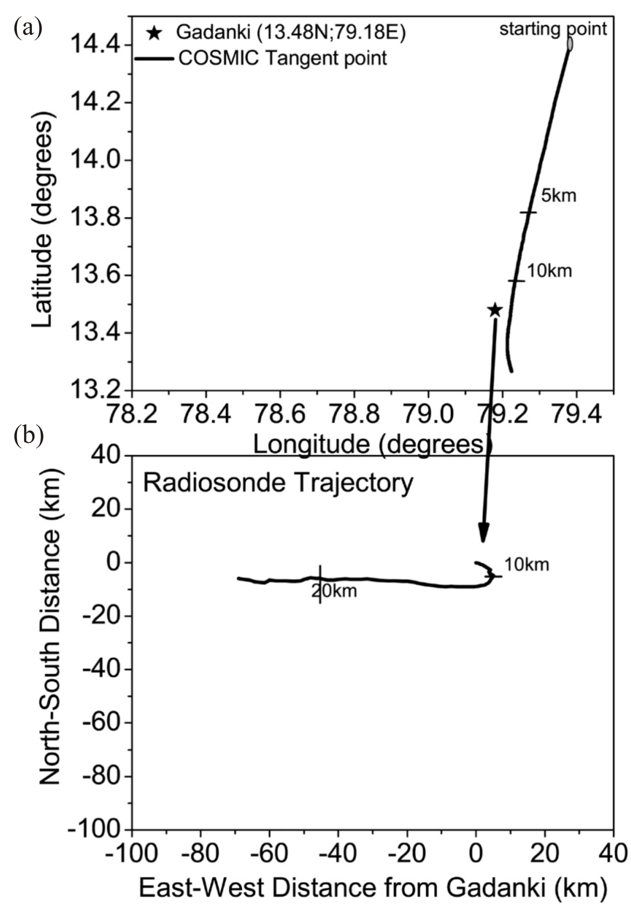

Fig. 2. The RO tangent point which occurred very close to Gadanki on 24 July 2006 (top panel). The location of radiosonde released is also shown in the figure. The balloon trajectory on the same day is shown in bottom panel.

where

$$Z = A\left(\frac{T_s}{T} - 1\right) + B \times \log10\left(\frac{T_s}{T}\right)$$
$$- C \times \left[10^{D\left(1 - \frac{T}{T_s}\right)} - 1\right] + F\left[10^{H\left(\frac{T_s}{T} - 1\right)} - 1\right] \qquad (3)$$

This is (Goff-Gratch 1946) equation over water, where A = -7.90298, B = 5.02808, C = -1.3816 * 10^{-7}, D = 11.344, F = 8.1328 * 10^{-3}, H = -3.49149, e_{st} (= 1013.246 mb) is saturation vapor pressure (e_s) at boiling point temperature (Ts = 373.16 K) at standard atmospheric pressure (1013.246 mb).

$$RH = \frac{e}{e_s} \times 100 \qquad (4)$$

RH is the relative humidity in percentage. Note that we have calculated the e_s only with respect to water as radiosonde can only sense with respect to water but not ice. For comparing with radiosonde, we have also estimated e_s with respect to water using COSMIC too.

From radiosonde data, refractivity is calculated from the temperature, pressure and vapor pressure using the first two terms in Eq. (1).

From COSMIC, the water vapor is estimated using the refractivity from COSMIC and pressure and temperature from 1D-var retrieval (hereafter called as COSMIC water vapor). We also incorporated the temperature and pressure from the Gadanki radiosonde observations in Eq. (2) to estimate water vapor (hereafter called as COSMIC derived water vapor). The relative humidity is calculated using Eqs. (2) and (4).

Further, the difference and fractional difference in refractivity are calculated as $N = N_{COSMIC} \quad N_{RS}$ and $N_{Fractional} \quad \frac{N}{N_{COSMIC}}$, respectively.

Mean difference and fractional mean difference of refractivity are calculated as $\frac{1}{n} \quad N$ and $\frac{1}{n} \quad \frac{N}{N_{COSMIC}}$, respectively, where n is the number of occultations.

The difference and fractional difference in temperature, water vapor and relative humidity are calculated as mentioned above substituting N by T, e, and RH.

4. RESULTS AND DISCUSSION

4.1 Comparison of Water Vapor between COSMIC and Radiosonde (Wet Region)

Fractional difference in refractivity (N), temperature (T1D where 1D stands for observations from 1D-var), pressure (P1D), water vapor pressure (WV1D), and relative humidity (RH1D) between COSMIC RO and radiosonde observations for the event that occurred on 24 July 2006 is shown in Fig. 3. As mentioned previously, for estimation of water vapor from GPS RO, one needs accurate information of temperature from an independent technique. In general, this temperature information is taken from 1D-var retrieval. Very small difference (< 0.3%) between the T1D used by COSMIC (1D-var) and the radiosonde can be noticed (Fig. 3b) except around 5 and 7 km on this day. Fractional difference in P1D is observed (Fig. 3c) to be 0.5% near 1 km

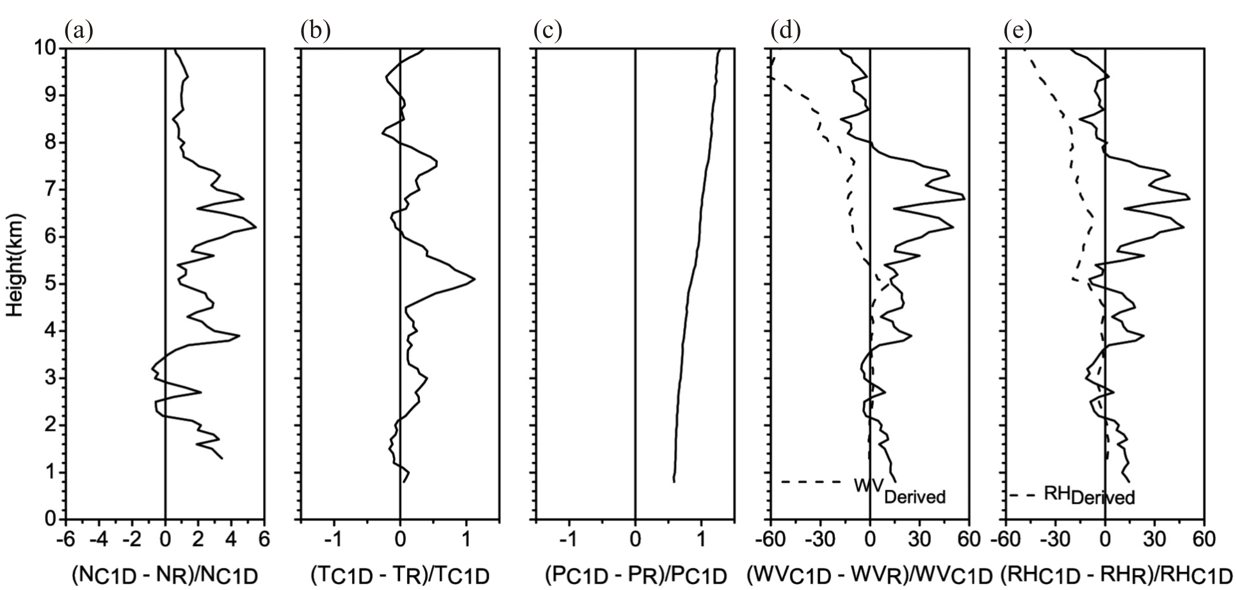

Fig. 3. Fractional difference between COSMIC RO event and radiosonde observations on 24 July 2006 in (a) refractivity, (b) temperature, (c) pressure, (d) water vapor pressure, and (e) relative humidity. Fractional difference in water vapor pressure and relative humidity observed by taking pressure and temperature from Gadanki radiosonde instead of 1D-var values is also plotted for comparison in (d) and (e), respectively.

and reached to about 1% around 10 km. Fractional WV1D (and also RH1D) difference is observed to be < 15% except between 6 - 8 km where it is found to be large (about 50%). It is interesting to note that the COSMIC WV1D and RH1D fractional difference is showing both positive and negative difference uniformly except between 5 - 8 km where it is showing consistent positive difference. However, this feature is not observed in the derived water vapor pressure and relative humidity where it is observed to be negative above 5 km.

A very good comparison between RH1D obtained from COSMIC and radiosonde both in trend and amplitude is noticed (not shown here) throughout the height region although there is some discrepancy between 6 and 8 km. In spite of the temperature difference of 3 - 4 K that exists between COSMIC and radiosonde around 5 km, note that a good comparison in WV1D and RH1D is noticed revealing that the temperature difference does not much affect the RH estimation. As mentioned earlier, we have incorporated the T from radiosonde (case 1) and T and P information from the radiosonde (case 2) for the event on 24 July 2006 and re-estimated the water vapor pressure (WV derived) and relative humidity (RH derived) fractional difference which is also included in Figs. 3d and e, respectively. No difference is noticed (not shown here) in case 1 when compared to RH as given by COSMIC. However, in case 2, small difference (< 10% up to 8 km) in the WV derived and RH derived can be noticed on this day.

We have also performed sensitivity test on the fractional difference in refractivity for the event that occurred on 24 July 2006 between COSMIC (1D-var) and radiosonde by changing T, P, RH, and WV in Eq. (1) and is shown in Fig. 4. By changing T from 1 to 5 K while keeping other variables constant, the change in N is observed to be 1 to 6% below 5 km (negative bias) and tends to zero around 10 km altitude and becomes 0.5 to 3% above (positive bias) again. Changing RH (WV) from 1% (1 mb) to 10% (5 mb) keeping other variables constant, results in a change in N of < 0.5% (< 0.2%) to 4% (20%) with decreasing (increasing) trend from surface to 10 km. The change is small (< 10%) in WV even for 5 mb difference up to 7 km. However, by changing P from 1 to 5 mb while keeping other variables constant, the

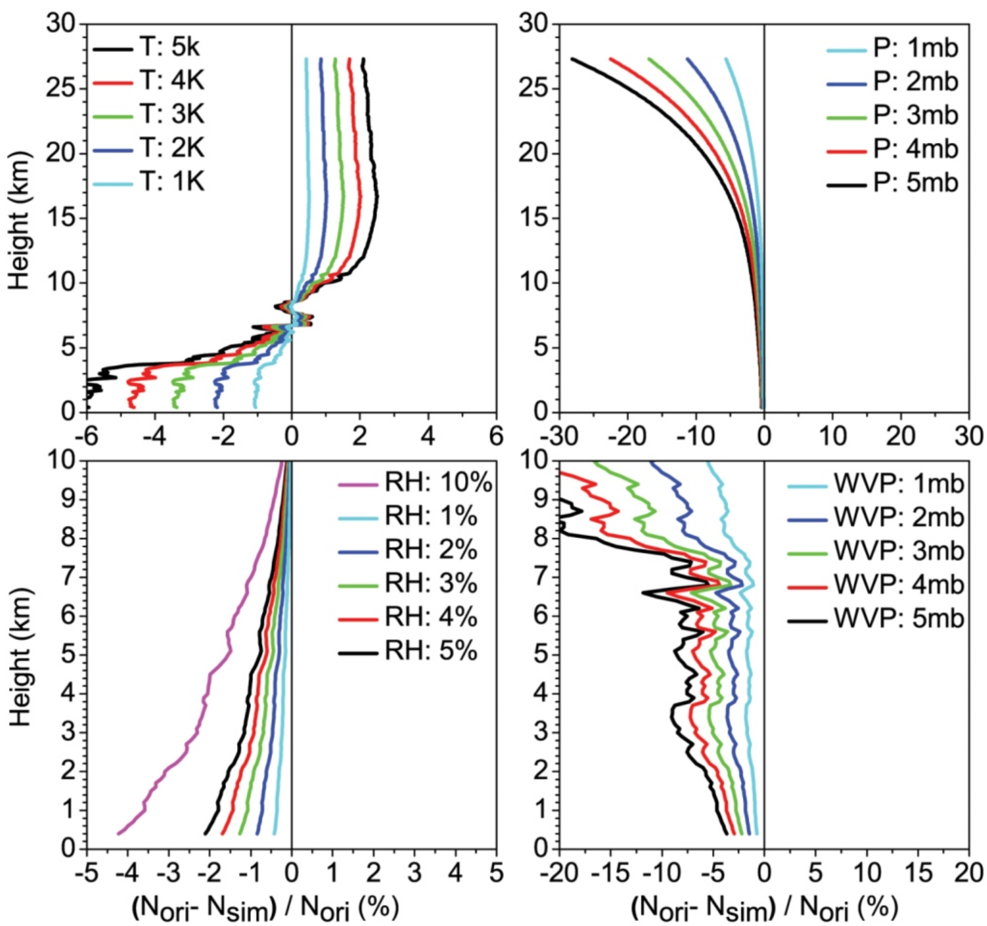

Fig. 4. Sensitivity test performed on the fractional refractivity observed on 24 July 2006 event between COSMIC wet data and radiosonde with changing the (a) temperature (T), (b) pressure (P), (c) relative humidity (RH), and (d) water vapor pressure (WP). The order of the increment in the T, P, RH, and WV is indicated in the respective figures.

change in N is observed to be exponentially increasing (negative bias) from < 0.1 to 30% from surface to 27 km. This suggests that small change in P estimation will lead to greater bias in the refractivity at higher heights.

The statistical mean difference in the N, T1D, P1D, WV1D, and RH1D between the COSMIC wet (1D-var data) and radiosonde (39 profiles) is shown in Figs. 5a - e and their corresponding fractional difference is presented in Figs. 5f - j. Note that number of occultations reaching down to surface is also plotted in Fig. 5a with axis on top. Large positive and negative difference in refractivity between COSMIC and radiosonde is noticed below 1 km and at 2 km, respectively (Fig. 5a). The mean difference in refractivity between COSMIC and radiosonde is about 2 N units near 2 km (negative bias) although larger difference (positive bias) is noticed near surface. One of the reasons for observing this large difference in refractivity below 3 km may be due to number of GPS RO profiles reaching down to surface is exponentially decreasing although the mean difference is less than 1 N unit above 5 km. The mean temperature difference between the COSMIC wet and radiosonde is less than 1 K above 2 km but about 2 K below it with colder bias (Fig. 5b) throughout the height region except at 1 km. About 1 mb atmospheric mean pressure difference has been noticed (Fig. 5c). The mean difference in water vapor pressure is less than 2 mb with positive difference except around 2 km height region (Fig. 5d). This difference in water vapor pressure is leading to about 5 to 15% in the relative humidity which is shown in Fig. 5e with more humidity in COSMIC profiles except around 2 km. Another interesting feature to be noticed is large difference in refractivity, water vapor pressure (or relative humidity) near 2 km altitude close to the top of atmospheric boundary layer.

The fractional mean difference presented in Figs. 5f - j also shows similar features in N and T1D. However, fractional difference in WV1D and RH1D is small (within 20%)

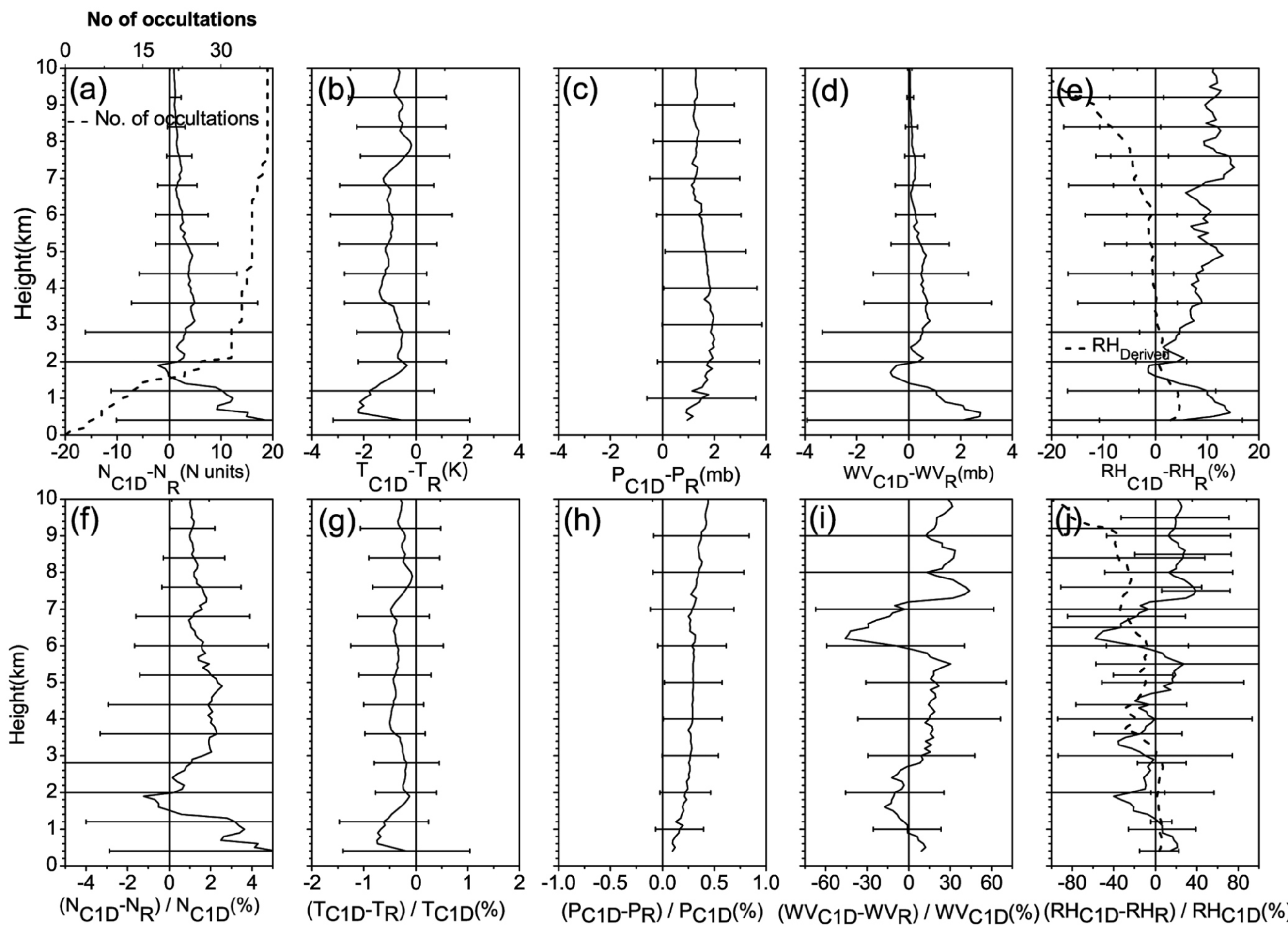

Fig. 5. Statistical mean difference, between COSMIC (1D-var) data and radiosonde in wet region for 39 overpasses with 3 latitude and longitude separation and 4 hours, of (a) refractivity, (b) temperature, (c) pressure, (d) water vapor pressure, and (e) relative humidity. The number of occultations reaching at various heights down below is also given in (a) with axis on the top. (f) - (j) same as (a) - (e) but for fractional difference. Note that statistical mean and fractional difference observed in relative humidity observed by taking pressure and temperature from Gadanki radiosonde instead of 1D-var values is also plotted for comparison in (e) and (j), respectively.

up to around 6 km but is high (positive between COSMIC and radiosonde except between 6 and 7 km) above it suggesting that COSMIC GPS RO wet profiles are more reliable up to 6 km (assuming radiosonde as the standard technique). Note that difference is again less above 7 km. It is often noticed that a strong layer between 6 and 8 km persistently observed over this latitude particularly during monsoon season (JJA). Derived RH (T and P information from the radiosonde) shown in Figs. 5e and j also shows excellent comparison up to 6 - 7 km similar to that observed by COSMIC (1D-var RH) and showed significant difference above, however, this difference is observed to be negative.

4.2 Comparison of Temperature between COSMIC and Radiosonde in Upper Troposphere and Lower Stratosphere (UTLS) (Dry Region)

The comparison between CHAMP and SAC-C RO data against global analysis from ECMWF and NCEP showed that RO soundings have excellent accuracy in the height range of 5 - 25 km (Kuo et al. 2004). In the present study validity of COSMIC RO dry data (typically above 10 km) is also tested using the 39 overpasses with the above mentioned selection criteria. As a typical case, overpass which occurred close by to Gadanki on 24 July 2006 is again used for detailed comparison between COSMIC RO dry data and radiosonde observations, which is shown in Fig. 6. It is found that the refractivity matches well with radiosonde (Fig. 6a). The difference in the N between COSMIC and radiosonde shows positive bias well within 1N unit. However the fractional mean difference in N shows 0 - 3% variations with increasing trend from 19 to 27 km (Fig. 6d). The temperature above 10 km fairly matches including the sharp changes near the tropopause height (Fig. 6b). But note that the COSMIC RO profile shows somewhat smoothed variations (since it is averaged over a 200 km horizontal distance) than radiosonde (in situ measurement) above the tropopause height. The fractional difference in temperature is within 2 K which agrees well with the temperature accuracy and shows more wavy behavior. This is expected due to gravity

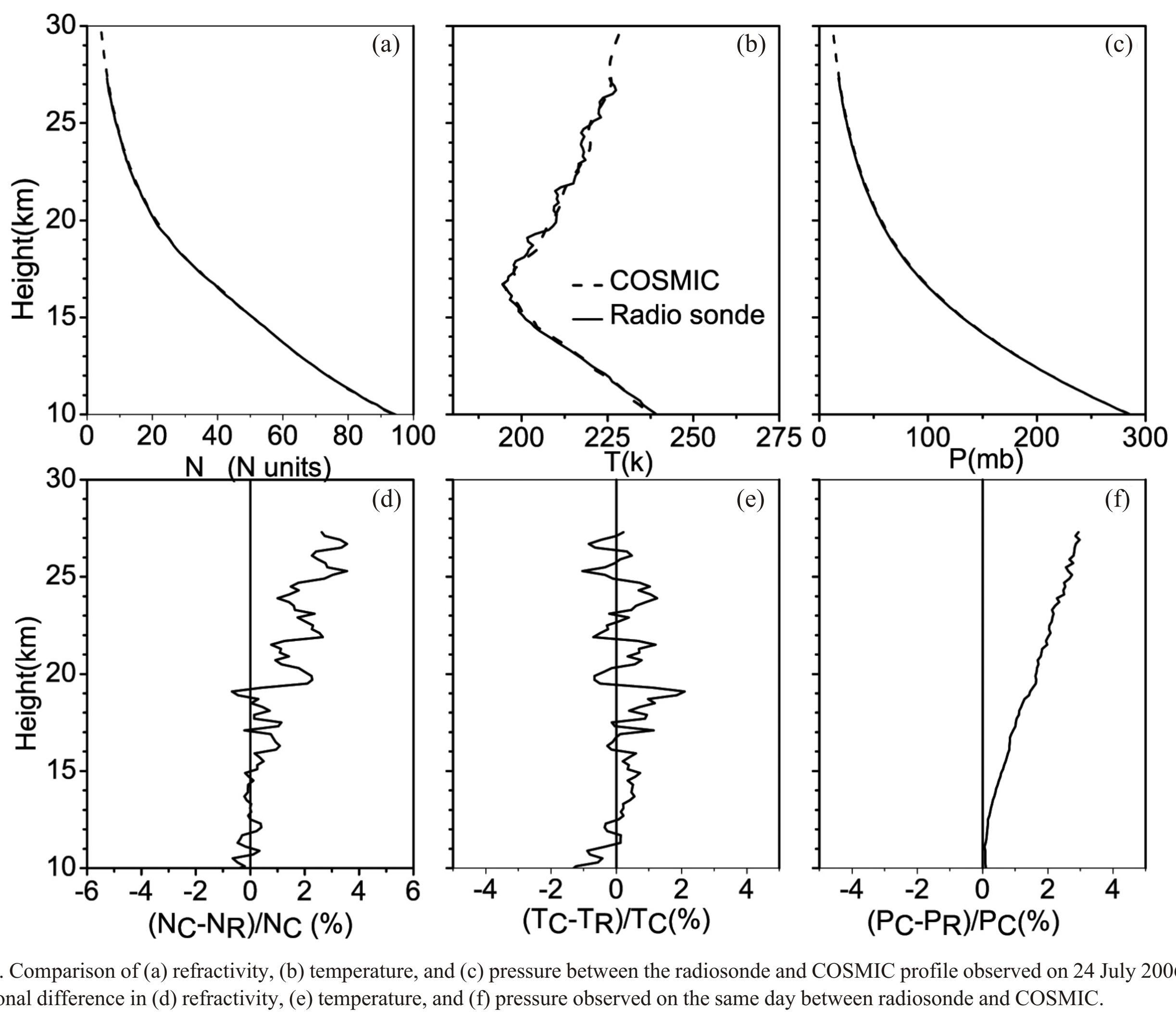

Fig. 6. Comparison of (a) refractivity, (b) temperature, and (c) pressure between the radiosonde and COSMIC profile observed on 24 July 2006. The fractional difference in (d) refractivity, (e) temperature, and (f) pressure observed on the same day between radiosonde and COSMIC.

wave activity generated due to convection and/wind shear (Beres et al. 2002) particularly during monsoon season over Gadanki. The RMS (root mean square) difference between 10 and 27 km is about 1.64 K on this day. Narayana Rao et al. (2007) have shown that there is a good agreement between the tropopause height obtained from the GPS RO measurements and radiosonde observations at different latitudes in northern and southern hemispheres. Note that variations in fractional pressure difference (Fig. 6f) resemble exactly with the variations that are observed in refractivity (Fig. 6d) but not temperature (Fig. 6e) suggesting that the precise estimation of pressure plays a crucial role in estimating the refractivity.

Statistical mean and fractional mean difference observed in N, T, and P between COSMIC and radiosonde estimated using all the 39 matches are shown in Figs. 7a - c and Figs. 7d - f, respectively. The number of balloons reaching different heights is also shown in the Fig. 7a with axis on the top. The mean difference in N (Fig. 7a) and T (Fig. 7b) is observed to be smaller than 0.5 N units and 1 K (except first few kilometers), respectively with standard deviation ranging from 1 - 1.5 N units and 2 - 4 K, respectively. Note that there is colder bias between COMSIC and radiosonde perhaps due to the assumption of dry atmosphere particularly in the first few kilometers (10 - 15 km) and also ignoring the presence of cirrus clouds which are prevalent in this height region in the tropics. The RMS difference in temperature is observed to be 0.64 K. The fractional mean difference in N (Fig. 7d) is found to be 1% up to the tropopause height and then increases up to 4% at 27 km. The fractional T difference (Fig. 7e) is found to be < 1%. Near the tropical tropopause at ~17.5 km, the mean T deviation is about 1 K with colder temperatures in COSMIC data. Once again note that variations in fractional P difference (Fig. 7f) resemble exactly with the variations that are observed in N (Fig. 7d) but not T (Fig. 7e) suggesting that pressure plays a key role in determining the refractivity than temperature. Wickert et al. (2001) have compared CHAMP observations with corresponding ECMWF profiles in the height range of 5 - 25 km and found excellent comparison within 1 K in both hemi-

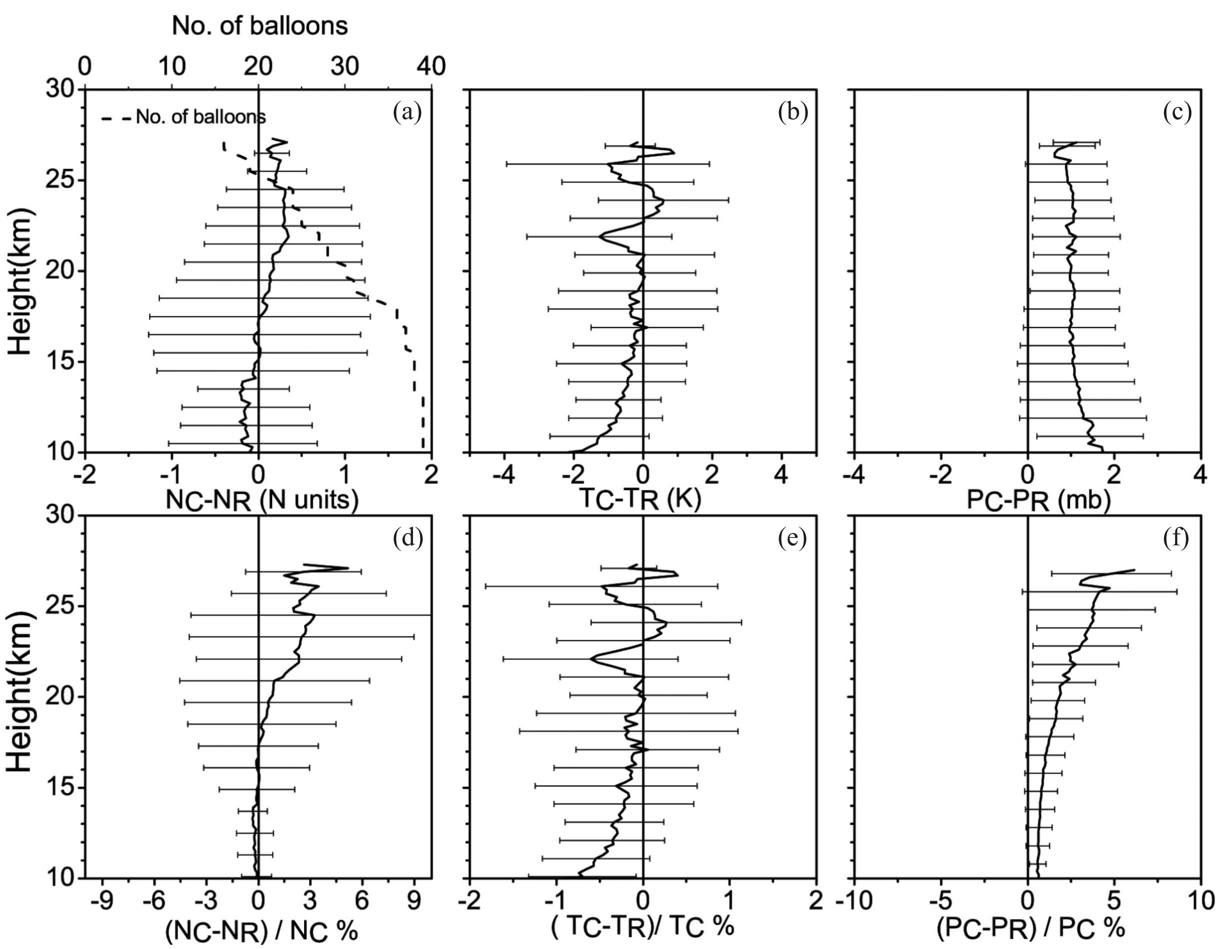

Fig. 7. Statistical mean difference between radiosonde and COSMIC (dry data) for 39 overpasses with 3 latitude and longitude separation and 4 hours of (a) refractivity, (b) temperature, and (c) pressure. The number of radiosonde balloons reaching maximum heights is also given in (a) with axis on top. (d) - (f) same as (a) - (c) but for fractional difference.

spheres, but with some negative bias at tropical latitudes similar to our results. Similar bias is also reported by Ratnam et al. (2004) using radiosonde and CHAMP (over Taiwan). Interestingly the large difference observed by Kuo et al. (2005) using routine radiosonde observations from India is not reflected in the profiles obtained using the Väisälä GPS radiosondes over Gadanki. This has been possible due to better vertical resolution of Väisälä GPS radiosonde and also due to better quality of the sensors and the data in comparison to the analyses that were available on standard pressure levels (IMD routine radiosonde).

4.3 Comparison of Temperature between COSMIC and Rayleigh Lidar in Middle and Upper Stratosphere

In this section, comparison of temperature between COSMIC and Rayleigh lidar observations in the height range of 30 to 40 km is presented. Figure 8 shows two typical examples of the comparison of COSMIC temperature profiles with radiosonde and lidar measurements taken at Gadanki on 20 August 2006 (Fig. 8a) and on 19 January 2007 (Fig. 8b). In general, COSMIC and ground-based radiosonde observed profiles are matching well as also noticed from the previous sections. There exists large difference below 5 - 10 km, which is due to water vapor and that occurs from incomplete temperature retrieval at these heights. Note that moisture content is larger during the first case which is taken during monsoon season and is less during second case taken during winter. This suggests that temperature information can be used right from 5 km onwards during winter seasons even in the tropical latitudes. Near the tropopause a very good comparison can be noticed in both the cases including sharp and broad nature of the tropopause. Above the tropopause height also a good comparison can be seen including the wavy nature. However, large discrepancy of about 10 - 15 K can be noticed on 20 August 2006 between 30 and 35 km between COSMIC and Gadanki lidar profiles although the difference tends to decrease above it and a good match is seen at around 40 km. Note that good consistency is observed between radiosonde and COSMIC profile on this day including the magnitude and trend but large shift/difference in temperature is observed between lidar and COSMIC at 30 km. The sudden shift is not expected since radiosonde and COSMIC profiles are going together and hence suggesting that there could be some problem in the lidar profile itself below 35 km. On 19 January 2007 also there exists a large difference between COSMIC and lidar profiles even though it is much better than the previous case. Note that on this day we used a very powerful laser source (30W) than that used on 20 August 2006 (10W). It does not mean that by using the powerful laser source the discrepancy can be reduced, as we also noticed large difference similar to 20 August 2006 case on the successive day i.e., 20 January 2007 (not shown here).

This kind of large difference has been noticed on almost all the days. The statistical mean difference along with standard deviation between COSMIC and Gadanki lidar mea-

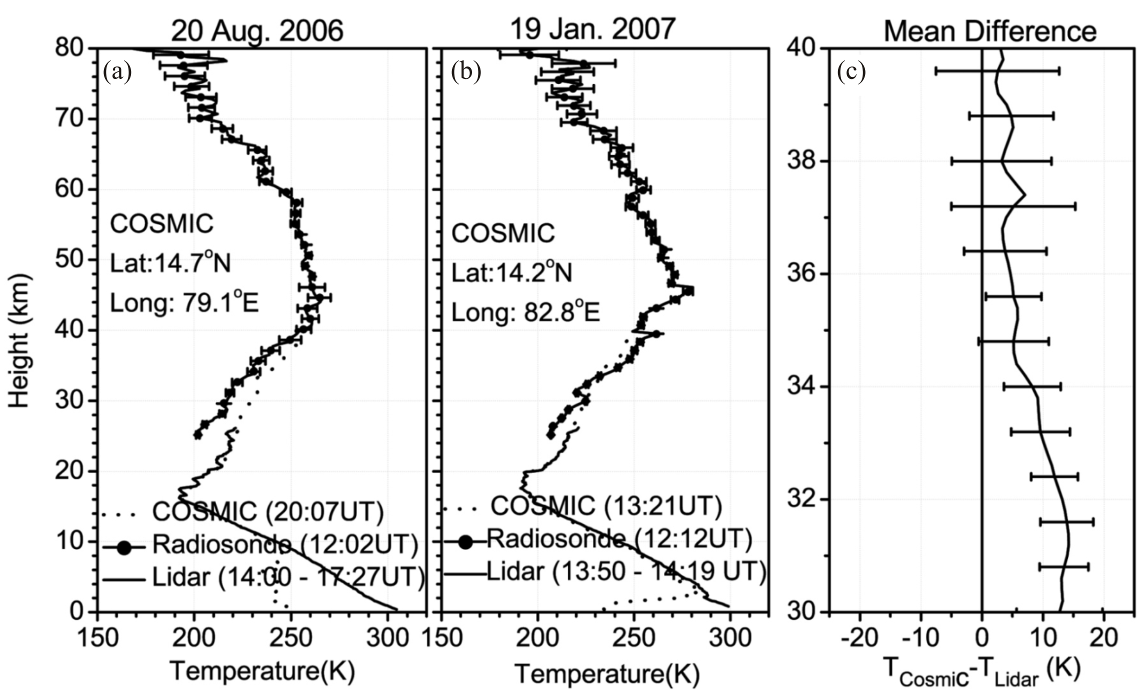

Fig. 8. Comparison between Gadanki radiosonde, COSMIC RO profile and Rayleigh lidar profile on (a) 20 August 2006, and (b) 19 January 2007. (c) Statistical comparison between COSMIC and Rayleigh lidar for 18 overpasses with 3 latitude and longitude separation and 4 hours.

surements is shown in Fig. 8c for all the 18 over passes. The mean difference is found to be 12 K at 30 km which reduced to 5 K at 35 km and less (3 - 4 K) above that height. This kind of large bias between CHAMP and Gadanki lidar is also reported by Ratnam et al. (2004). Similar to that reported by Ratnam et al. (2004), there always exists colder bias in the lidar measurements. A possible reason for the observed large discrepancy could be due to the presence of aerosol concentration up to 35 km which will contaminate the temperature retrieval from lidar. However, this is not possible unless a large volcanic activity took place which has not taken place in recent past. In case of COSMIC, the correction due to the ionospheric residuals may also create a problem above 35 km, and sometimes even from 30 km upwards as suggested by Rocken et al. (1997) and Syndergaard (2000). But in the present case it may not be true as a good consistency in the trend is observed from the co-located radiosonde observations although there is no overlap region between the two. However, since the number of observations with nearest coincidence is very small, a more careful validation based on a larger dataset is required not only at this site but also elsewhere before arriving at a conclusion as there could be inaccuracies in the temperature estimation both in COSMIC and Lidar observations. It is also planned to launch high altitude balloons reaching 42 - 43 km at this site very soon and hope better conclusion can be drawn from the comparisons with all the three instruments (COSMIC, Lidar, and high altitude balloon) for the data in the height range of 30 to 40 km.

5. SUMMARY AND CONCLUSIONS

We have conducted intensive radiosonde soundings (Väisälä) during the overpass of COSMIC over a tropical station, Gadanki to compare N, WV, and T profiles from COSMIC. In addition, we operated co-located Nd: YAG Rayleigh lidar during the overpasses. A total of 142 overpasses have occurred after the day 193 in which 39 occurred within 300 km distance from Gadanki. A very good comparison between radiosonde and COSMIC RO has been noticed. Detailed analysis has been done for the event that occurred very close by to Gadanki on 24 July 2006 with special emphasis on WV retrieval. Although good consistency in the WV1D is observed between COSMIC and radiosonde observations up to 6 - 7 km, this difference is much reduced when T and P from radiosonde instead of T1D from COSMIC (1D-var) are used. A very good comparison both in trend and magnitude has been observed on this day below 5 km. Although there is a T1D difference of 1 - 2 K between radiosonde and that used by COSMIC profiles, the RH1D difference is not more than 5 - 10% at 5 km. However, fractional difference (statistical for 39 overpasses) in WV1D and RH1D is small (within 20%) up to around 6 - 7 km but is high (positive between COSMIC and radiosonde) above it suggesting that COSMIC GPS RO wet profiles are more accurate up to 6 - 7 km (assuming radiosonde is standard technique). Derived RH (T and P information from the radiosonde) also shows excellent comparison up to 6 - 7 km similar to that observed by COSMIC (1D-var RH) and showed significant difference above, however, this difference is observed to be negative.

We have also performed the sensitivity test on the fractional difference in N for the event that occurred on 24 July 2006 between COSMIC (1D-var) and radiosonde by changing T, P, RH, and WV in Eq. (1). It is observed that small change in P estimation leads to greater bias in the N at higher heights but not in other variables in Eq. (1) suggesting that pressure plays a key role in determining the refractivity than temperature.

A very good comparison in dry T is also noticed above 10 km between COSMIC and radiosonde observations with mean difference of only 1 K and standard deviation of ~2 K. It is suggested to consider the dry region from above 13 km onwards for this tropical latitude as convection and humidity are prevalent generally up to about 13 km on several occasions. The RMS difference in the temperature between 10 and 27 km is observed to be 0.64 K. This kind of good consistency is not observed by the routine radiosonde observations of IMD as reported by Kuo et al. (2005). COSMIC and Lidar temperature measurements have been compared in the height range of 30 to 40 km. There exists a large difference of about 12 K in T at 30 km which reduced to 5 K at 35 km and 3 - 4 K above it between COSMIC profiles and Gadanki Lidar measurements. Presence of large aerosol concentrations up to 35 km can contaminate the retrieval of temperature from lidar. However, large concentrations of aerosols up to 35 km are unlikely to be present unless there is a major volcanic eruption. But there is no evidence of a major volcanic eruption in the recent past. The propagation of ionospheric residuals down to 35 - 40 km may not be the issue in the present case as a good consistency is observed between radiosonde and COSMIC although there is no overlap region between the two. However, it may be premature to come to a conclusion as the number of cases considered is small (only 18) and should be compared with other lidars located elsewhere too. It is also planned to launch high altitude balloons reaching 42 - 43 km from this site to get a better picture on the validation of temperature between 30 and 40 km.

Many other effects should also be considered while attributing to the differences in wet and dry regions between ground based and satellite borne measurements. For example, ground based instruments generally provide vertical profiles more or less directly above the station, providing essentially point measurements. In contrast, GPS RO give profiles which are weighted average along the line of sight. Another difficulty is that coincidence of GPS RO and ground based instruments is never exact, either in space or in time.

There are also uncertainties associated with the averaging procedures employed by the different measurement techniques.

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