A New Technique for Estimation of Lower-Tropospheric Temperature and Water Vapor Profiles from Radio Occultation Refractivity

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ABSTRACT

An empirical technique is proposed to obtain temperature and humidity profiles over the tropics using radio occultation refractivity profiles and surface/available lower-altitude temperature and pressure measurements over humid tropical regions. The technique is tested on a large number of diverse radiosonde-derived refractivity profiles over the tropics (30°S–30°N) and selected Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) radio occultation refractivity profiles that have collocated radiosonde observations over the region 10°S–30°N during the boreal summer of 2006. In a number of cases, the results were in good agreement with the collocated radiosonde data. The error statistics of temperature and humidity profiles obtained from the proposed technique are discussed and compared with the previously published results from another technique and also with the results of a one-dimensional variational data assimilation (1DVAR) technique given with COSMIC data. It is found that the previously published results and proposed technique are marginally better (worse) in reproducing observed relative humidity (specific humidity) when compared to the 1DVAR technique. The proposed new technique is applied on COSMIC refractivity profiles over the Bay of Bengal during summer 2007 to derive changes in vertical thermal and moisture changes in the troposphere between active and break phases of the monsoon pattern and many of the observed features are captured reasonably well.

1. Introduction

Estimation of atmospheric temperature, pressure, and humidity in the lower troposphere from radio occultation refractivity profiles is an active area of current research. The radio occultation technique refers to the measurement of global positioning system–Global Navigation Satellite System (GPS–GNSS) signal phase delays recorded on a space-qualified GPS–GNSS receiver mounted on a low-earth-orbiting satellite (LEO). The phase delay due to a neutral atmosphere between the GPS–GNSS satellite and LEO can be converted to bending angle and refractivity profiles under the assumption of a spherically symmetric hydrostatic atmosphere (e.g., Kursinski et al. 1997; Yunck et al. 2000). Since the time radio occultation technique was demonstrated during the proof-of-concept meteorological applications of GPS (GPS/MET) experiment (Ware et al. 1996), there have been many improvements in currently operational missions, such as Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC; Anthes et al. 2008). Analysis of COSMIC results indicates a substantial improvement in the accuracy and precision of refractivity profiles, especially over the tropics and mainly as a result of improved tracking of radio occultation signals and better inversion algorithms compared to the standard geometric-optics-based technique (Sokolovskiy 2001; Jensen et al. 2003; Kuo et al. 2004; Sokolovskiy et al. 2006). These improvements also resulted in over 80% of the occultation measurements in COSMIC penetrating the lower troposphere closer to the surface than previous missions like the Challenging Minisatellite Payload (CHAMP; Anthes et al. 2008; Hajj et al. 2004). Radio occultation measurements of vertical profiles of refractivity are used to derive vertical profiles of atmospheric pressure, temperature, and water vapor pressure. Variational assimilation of the radio occultation...
refractivity or bending angle in numerical weather prediction models is regarded as a standard procedure for deriving temperature, pressure, and water vapor pressure fields (e.g., Gorbunov and Sokolovskiy 1993; Healy and Eyre 2000; Palmer et al. 2000; Gorbunov and Kornblueh 2003; von Engeln et al. 2003). The COSMIC mission operationally uses the 1D variational data assimilation technique (1DVAR; Healy and Eyre 2000; Palmer et al. 2000) to retrieve temperature, pressure, and water vapor pressure profiles. One must note that the variational data assimilation schemes are computationally expensive and one cannot rule out that they may be affected by atmospheric model biases (especially over open oceans where upper-air temperature observations are scarce).

As an additional measure, it is desirable to have alternate techniques when using reanalysis fields, and therefore the corresponding atmospheric model bias is minimal. One such technique was presented by O’Sullivan et al. (2000), where European Centre for Medium-Range Weather Forecasts (ECMWF) analyses of 1000-hPa temperature and pressure were used as the only external information in deriving profiles of temperature, pressure, and water vapor from GPS/MET refractivity profiles. O’Sullivan et al.’s (2000) technique relies on the assumption that temperature may be parameterized as a quadratic function of the natural logarithm of pressure.

We propose an empirical technique to derive the temperature, pressure, and humidity information from radio occultation refractivity profiles, with the surface temperature and pressure as additional information based on an examination of a large number of diverse radiosonde profiles over the tropical region. In our technique, we parameterize temperature profiles using a procedure whose inputs are the surface temperature and pressure, as well as the refractivity profile. We use this temperature profile as an approximation of the actual temperature profile and then derive pressure and water vapor pressure profiles from the refractivity profile. We give a description of our technique and its application to a large number of diverse radiosonde-derived refractivity profiles and radio occultation measurements of refractivity profiles from the COSMIC mission (Rocken et al. 2000; Schreiner et al. 2007; Anthes et al. 2008) over the tropics during May–September 2006, and the error statistics are discussed and compared with O’Sullivan et al.’s (2000) technique and also with the COSMIC 1DVAR results. We note here that temperature is fairly stable on daily time scales over the tropics and there is also a significant moisture signature present. As we have used radiosonde-derived refractivity and its associated temperature statistics mainly over the tropics as empirical information in the technique, our method may have limited applicability outside the tropics. We also apply our technique on COSMIC refractivity profiles over the Bay of Bengal during May–September 2007 to derive information on vertical thermal and moisture changes between the active and break phases of the monsoon cycle and compare our findings with the results from the standard 1DVAR technique given on the COSMIC Web site (http://cosmic-io.cosmic.ucar.edu) and those of O’Sullivan et al. (2000). The strengths and limitations, as well as the scope for improvements, of our technique are discussed.

2. Description of the technique

Neutral atmospheric refractivity is related to pressure in hectopascals (P), temperature in kelvins (T), and water vapor partial pressure in hectopascals (e) by the following equation (Smith and Weintraub 1953):

\[ N = c_1 \frac{P}{T} + c_2 \frac{e}{T^2}, \]

(1)

where \( c_1 = 77.6 \) K hPa\(^{-1} \) and \( c_2 = 3.73 \times 10^5 \) K\(^2 \) hPa\(^{-1} \).

Using hydrostatic approximation, we can write the following equation for pressure \( P \) (Kursinski et al. 1997):

\[
\begin{align*}
P(z) &= \int_z^\infty \left[ -\frac{g m_d N}{77.6 R} + \frac{3.73 \times 10^5 g m_d e}{77.6 R T^2} \\
&\quad+ \frac{g (m_d - m_w) e}{R T} \right] dz,
\end{align*}
\]

(2)

where \( z \) is the altitude, \( m_d \) the molecular mass of dry air, \( m_w \) the molecular mass of water, \( R \) the universal gas constant, and \( g \) the acceleration due to gravity. If water vapor pressure can be ignored, then one can solve Eqs. (1) and (2) for temperature and pressure (Kursinski et al. 1997). One takes a climatological or model-derived temperature at some higher altitude (typically 50–60 km) as the boundary condition. The temperatures so derived are known as dry temperatures (Kursinski et al. 1997). The dry temperatures deviate significantly from actual temperatures in the troposphere below \( \sim 10–12 \) km where the water vapor presence is nonnegligible, especially in the tropical regions. One can detect the cold-point tropopause using dry temperatures over the tropics without much problem. Below the tropopause, when dry temperature begin to approach \( \sim 230 \) K, the corresponding height may be treated as being the water vapor point altitude (\( z_w \)), below which water vapor presence is dominant. This is because even if the atmosphere is saturated at temperatures of 250 K or lower, the resulting water vapor does not affect the dry retrieval and hence dry temperatures may be approximated as actual temperatures to within

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2 K (O’Sullivan et al. 2000). If we were to separate the two terms of the refractivity in Eq. (1), then we could solve for $P$, $T$, and $e$ using Eqs. (3)–(5) iteratively with the boundary condition that $e$ is 0 at $z_w$ and the dry temperature and pressure are approximated as the actual temperature and pressure at $z_w$:

$$P = \int_{z}^{z_w} \frac{g}{R} \frac{N_1 m_d}{77.6} + \frac{e(m_w - m_d)}{T} \, dz,$$  \hspace{1cm} (3)

$$T = c_1 \frac{P}{N_1}, \quad \text{and}$$

$$e = \frac{N_2 T^2}{c_2},$$  \hspace{1cm} (5)

where $N_1$ and $N_2$ are the first two terms of the refractivity in Eq. (1).

The empirical technique we have devised consists of the following steps.

1) Using surface pressure and temperature, and refractivity at the water vapor point ($z_w$), we estimate the first term of refractivity ($N_1$) as an exponential function of height [i.e., a log-linear fit of $N_1$ (denoted as $N_{1llf}$) with height; i.e., $\ln N_{1llf}(z) = a + bz$, where $a$ and $b$ are determined using values at the surface (using surface pressure and temperature) and the water vapor point (where the contribution of $N_2$ is assumed to be negligible)].

Then, using $N_{1llf}$ and $N_2 = N-N_{1llf}$ profiles, we solve for $P$, $T$, and $e$ using Eqs. (3)–(5) iteratively from the water vapor point to the lowest level where refractivity is available. We refer to the resulting $P$, $T$, and $e$ as the first-cut retrieval as the separation of the two terms of the refractivity is very crude.

2) We take an average of the first-cut retrieval $T$ and a linear fit of $T$ using surface and water vapor point values (where the dry temperature is taken to be an approximation for the actual temperature). We call this the refined temperature. The refined temperature is taken to be an approximation for the actual temperature.

3) Using the refined temperature profile, we solve for $P$ and $e$ using Eqs. (1) and (2) iteratively (Kursinski and Hajj 2001) from the water vapor point to the lowest altitude up to which the refractivity is available with zero water vapor pressure at $z_w$.

The refined temperature and $P$ and $e$ obtained using step 3 are the final products of our empirical technique. The above empirical procedure is arrived at after examining a large number of diverse radiosonde-derived refractivity profiles. We applied this method to a large number of diverse radiosonde refractivity profiles for which $P$, $T$, and $e$ are known (or preset) and hence the expected accuracy and error estimates are first made before their application to radio occultation refractivity profiles.

3. Data

We use high vertical resolution radiosonde profiles of temperature, pressure, and water vapor pressure from different sources for validation of the empirical technique given in the previous section. The radiosonde datasets used in this study are composed of those from special campaigns such as the Bay of Bengal Monsoon Experiment (BOBMEX) campaign during August 1999 (Bhat et al. 2001); special launches over Gadanki, India (Rao et al. 2009), which are meant to validate Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) radio occultation refractivity profiles during 2006–07; and the standard radiosonde dataset over the tropics (between 30°S and 30°N) known as the Thermodynamic Initial Guess Retrieval (TIGR), which is used in algorithm development for temperature and humidity retrievals from infrared sounders (Seemann et al. 2003). Figure 1 shows locations of TIGR radiosonde profiles used in this study. These profiles are distributed over the tropical region (30°S–30°N) and were chosen particularly for their diversity. Also, the measurement times of the TIGR radiosonde profiles span more than a decade and are thus diverse in both time and space, in addition to the profile features.

![Fig. 1. Locations of the 5040 TIGR radiosonde profiles used to validate our empirical technique.](image-url)
FIG. 2. (a) An example of the temperatures, pressures, and specific and RHs retrieved along with actual values using the RT and OS techniques on TIGR radiosonde refractivity profiles. Actual (radiosonde) temperatures are represented by symbols. The RT technique is denoted by a solid line, the OS technique by a dashed line, and dry temperatures and pressure denoted by a dotted line. (b) Same as in (a) but for a relatively more humid tropospheric case.
We also test the technique on COSMIC refractivity profiles during May to September 2006 and compare the results with collocated radiosonde and NCEP reanalysis data (Kalnay et al. 1996).

4. Application of the technique on radiosonde-derived refractivity profiles

We have examined the $N$, $T$, $P$, and $e$ profiles from a large number of diverse radiosonde data sources over the tropics, as mentioned in the previous section. All the radiosonde data examined here have profiles that are well above the tropopause. Starting from the topmost altitude pressure boundary conditions, we calculated a “dry” temperature profile (i.e., assuming the “wet” contribution to be zero at all altitudes) (Kursinski et al. 1997). The dry temperature profile differs from the actual profile at an altitude where near linearity with respect to the height of the dry temperature profile also usually deviates. This altitude some times demarcates the moist troposphere from the dry upper troposphere and is close to the altitude referred to as the water vapor point (O’Sullivan et al. 2000). We take the height, when we first encounter the dry temperature at $\sim 230$ K below the tropopause, as a conservative estimate of the water vapor point, as neglecting the water vapor at temperatures below 250 K does not introduce significant differences between the dry and actual temperatures (O’Sullivan et al. 2000). It is also worth noting that the dry temperature generally has a cold bias below the water vapor point. This is because of overestimation of the hydrostatic term and the total neglect of the wet term below the water vapor point in the calculation of dry temperatures (Kursinski et al. 1997). On the contrary, if the hydrostatic term were to be underestimated, the resulting temperature retrieval would be warm biased. We find that $N_{dry}$ is generally underestimated between the water vapor point height and the surface in all of the radiosonde profiles we examined, and hence there was a warm bias in the first-cut retrievals. Considering that we have found this result in thousands of profiles over the tropics, we can assume it is a generally valid fact in an empirical sense.

Our empirical method requires that the surface or a lower-altitude temperature and pressure be known. Another method based on the estimation of temperature as a quadratic function of the natural logarithm of pressure was put forth by O’Sullivan et al. (2000), who also used the surface or lower-altitude pressure and temperature as auxiliary information. Our approach is different from that of O’Sullivan et al. (2000) in that we
first estimate a smooth temperature (refined temperature in section 2) profile largely by empirical means and then retrieve the $P$ and $e$ profiles. We applied the procedure described in section 2, to derive $P$, $T$, and $e$ and, subsequently, relative humidity values using $T$ and $e$ from the radiosonde refractivity profiles mentioned in the previous section [We refer to our method as the refined temperature (RT) approach hereafter.] As we start our integration from the water vapor point, we get $P$ and $e$ profiles up to the level where the refractivity measurements are available in the case of radio occultation measurements. Thus, it is not necessary for the actual radio occultation refractivity profiles to be available down to the surface, but only the surface temperature and pressure profiles from meteorological measurements/analysis are required for estimating $N_1$ as an exponential (log-linear) function of altitude and are used to derive the first-cut retrievals of pressure, temperature, and water vapor partial pressure. Once we detect the water vapor point ($z_w$), we applied the procedure explained in section 2 to arrive at the $T$, $P$, and $e$ values, as well as the relative humidity value. We also applied O’Sullivan et al.’s (2000) technique (hereafter referred to as OS) with the only minor difference being that we chose the water vapor point as described in section 2 and compared it with our results. O’Sullivan et al. (2000) chose their water vapor point in a different way. Our choice of water vapor point appears to be good at least over the tropics, as will be shown in the comparison statistics later. Figures 2a and 2b show two cases of temperature, specific humidity, relative humidity, and pressure profiles obtained using the RT and OS methods.
compared with the actual values for radiosonde-derived refractivity profiles. Figure 2a is a relatively dry case with its maximum specific humidity not exceeding 3 g kg\(^{-1}\). The OS method gives noticeably better results than our method. Our method also gave specific humidity and relative humidity results that were not too much different from those of OS. In such dry cases, refined temperatures do not approximate the actual temperature very well. Figure 2b shows a relatively wet troposphere case where the maximum specific humidity is \(\sim 15\) g kg\(^{-1}\). In this case, the RT method gives a better temperature profile compared to OS. Despite a warm bias in temperature, the OS method gives specific and relative humidities that are very close to the observations and the RT method. We note here that the OS technique is not checked on radiosonde-derived refractivity to our knowledge. O’Sullivan et al. (2000) give their results for GPS/MET refractivity profiles (Ware et al. 1996) compared to ECMWF–NCEP.

We further show a histogram plot of refined, linear fit, and first-cut retrieval temperature deviations from the actual values of 5040 TIGR radiosonde profiles (Fig. 3), which clearly shows that the refined temperature profile is a good approximation to the actual temperature profile. More than 75% of the time, the refined temperature shows an absolute error of less than 2.5 K. Similar results were obtained for other radiosonde-derived refractivity profiles mentioned previously (not shown). The specific and relative humidity profiles retrieved using refined temperature and refractivity profiles agreed reasonably well with the actual values for all the radiosonde-derived refractivity profiles examined in this study. Figure 4a shows the mean deviation and the root-mean-square errors (RMSEs) of the OS and RT techniques with respect to the radiosonde-measured values of temperature, specific humidity, pressure, and relative humidity for 5040 TIGR radiosonde refractivity profiles. It can be seen that temperature RMSEs are
generally below 3 K, good enough to retrieve the specific and relative humidities to a good accuracy as there are no errors in refractivity since we are dealing with radiosonde-derived refractivities for which we know the temperature, pressure, and water vapor pressure. Figure 4a also show that the relative humidity RMSEs are ~5% over most of lower troposphere. Large RMSEs for relative humidity at upper levels are mainly due to the
assumption of a zero water vapor boundary condition at the water vapor point and may be improved with the assumption of some background water vapor at the water vapor point. We note here that the OS technique gives better relative and specific humidities, especially in the upper troposphere. It is thus evident that the RT as well as the OS techniques may be potentially applicable to radio occultation–derived refractivity profiles for the humid tropical atmosphere cases in the lower troposphere. We further note that there is a warm bias in OS temperatures whereas RT temperatures are slightly cold biased in the upper troposphere. The OS technique–retrieved pressure profile has better RMSEs than that from RT. Thus, it appears that even though there may be a large warm bias in some cases in OS, the resulting error in the water vapor retrieval is somewhat compensated by the smaller error in the OS pressure retrieval. To further gain insight into this aspect, we chose a subset of TIGR radiosonde profiles where the maximum specific humidity is greater than or equal to 15 g Kg\(^{-1}\). The error statistics for this subset are shown in Fig. 4b. It can be seen that the RT temperature and pressure RMSEs are now slightly better by excluding the relatively dry profiles. In the case of OS, the warm bias and RMSEs in temperature worsen but still give better specific humidity than RT because of better pressure profile retrieval. The relative humidity RMSEs of RT are slightly better than those from OS in the lower troposphere, probably due to error correlations in temperature and specific humidity.

5. Application to radio-occultation-derived refractivity profiles

Having examined our technique over a large number of radiosonde-derived refractivity profiles, we now apply the technique to a number of COSMIC radio occultation refractivity profiles (Rocken et al. 2000; Schreiner et al. 2007) that also have collocated radiosonde temperature, pressure, and water vapor pressure.
profiles. We chose the region under study to be 10°S–30°N during boreal summer 2006. This encompasses the equatorial region and Northern Hemisphere tropics, which are likely to be humid during boreal summer. Having checked the technique with a large number of radiosonde data, we believe this choice to be sufficient enough to prove the potential utility of the technique on radio occultation refractivity profiles for the humid tropical regions. These data are taken from the COSMIC Web site (http://cosmic-io.cosmic.ucar.edu). We note that the refractivity profiles from COSMIC did not always match those from collocated radiosonde measurements. There were noticeable differences in many cases. This may be due to representation errors between the two datasets or time and space offsets arising out of collocation, refractivity retrieval errors, etc. It is beyond the scope of this paper to discuss these issues. We have chosen 663 COSMIC refractivity profiles for which collocated radiosonde data have at least nine refractivity values between the surface and the water vapor point.

The tangent-point latitude–longitude locations of these profiles close to the surface are shown in Fig. 5. Temperature, specific and relative humidity, and pressure profiles retrieved using RT, OS, and the COSMIC 1DVAR technique (given on the COSMIC Web site), as well as radiosonde values, are shown for three typical cases in Figs. 6a–c. In one case during 29 May 2006 (Fig. 6a), the RT and COSMIC 1DVAR temperatures are closer to the radiosonde values compared to OS. All three techniques give specific and relative humidities that are closer to the actual values. The pressure retrievals in OS and the COSMIC 1DVAR technique are better than in RT. One can notice large deviations in the upper troposphere in the vicinity of the water vapor point. As we have mentioned, this is due to the zero water vapor boundary condition at the water vapor point. In another case during 20 May 2006 (Fig. 6b), the OS temperature profile is better than that in RT. In this case, the specific humidity is relatively less (≈4 g Kg⁻¹). In another case during 20 June 2006 (Fig. 6c), there is a

Fig. 6. (Continued)
large temperature inversion at ~6.5 km, also marked by a sharp humidity gradient. The OS and COSMIC 1DVAR technique capture the specific and relative humidities' sharp variation better than RT. In fact that OS technique gives temperatures that are almost the same as those observed down to the altitude of the sharp temperature inversion despite the fact that the water vapor point we have chosen is at a higher altitude of ~10 km. O’Sullivan et al. (2000) suggest that water vapor point is to be brought as close to the lower altitudes as possible in order to reduce inaccuracies in the estimation of temperature as a quadratic of the natural logarithm of pressure. We find that the issue of water vapor point altitude is not so important in relatively less humid cases and in almost all cases the O’Sullivan method tends to give better water vapor profiles mainly because of the better pressure profiles retrieved.

The mean deviation and RMSE between the COSMIC and radiosonde results (and NCEP) are shown in Fig. 7. The COSMIC refractivity has RMSEs ranging from 5 to 20 N units in the lower troposphere (0.4 to 10 km in altitude) with respect to the radiosonde data, and the RMSEs with respect to NCEP are noticeably smaller in the upper troposphere. Figures 8a and 8b show comparison statistics of the RT, OS, and COSMIC 1DVAR retrievals with respect to radiosonde and NCEP data, respectively. RMSE values for relative humidity are higher compared to those obtained from radiosonde refractivity profiles discussed in the previous section using the RT and OS technique mainly because of refractivity differences between the radiosonde and COSMIC results. It thus looks like refractivity errors/differences translate largely to humidity and pressure errors/differences. The OS technique gives pressure RMSEs with respect to radiosonde and NCEP that are almost similar to the COSMIC 1DVAR technique, further supporting the inference gained from radiosonde refractivity profiles. Temperature RMSEs from the OS technique with respect to both radiosonde and NCEP show large warm biases and RMSEs. If one were to find ways to correct this bias, it would appear that the OS technique might give better temperature profiles, as well as lower RMSEs.
However, as there appears to be a variable warm bias in OS depending on the moisture content in the troposphere, more studies are required in this regard. All three techniques give similar specific and relative humidity mean deviations and RMSEs. The specific humidity RMSEs from the COSMIC 1DVAR technique with respect to the radiosonde values. Thin (thick) solid, dashed, and dotted lines indicate the MDEV (RMSE) of the RT, OS, and COSMIC 1DVAR techniques. On the contrary, the RT and OS relative humidity retrieval RMSEs with respect to the radiosonde and NCEP results are better than those with COSMIC 1DVAR, indicating there may be some error correlation between the temperature and specific humidity retrievals in RT and OS (Figs. 8a and 8b). Thus, using parameterized temperature profiles, the RT and OS techniques are able to give reasonably good estimates of specific and relative humidity profiles from radio occultation refractivity profiles.
6. A case study over the Bay of Bengal

We apply the OS and RT techniques to the retrieval of temperature and specific and relative humidity profiles from COSMIC refractivity profiles over the Bay of Bengal (15°–20°N, 80°–90°E) during summer 2007. We mainly focus on vertical thermal and moisture changes between active and break phase of the monsoon. It is known from the observational radiosonde campaign during summer 1999 that the largest moisture changes occur at midtropospheric altitudes and the atmosphere is relatively warm above 6-km altitude during the active phase of the monsoon (Bhat et al. 2002). Based on whether the outgoing longwave radiation (Liebmann and Smith 1996) is less than 180 W m$^{-2}$ (greater than 220 W m$^{-2}$), we categorized the COSMIC refractivity profiles as active (break) cases. There were 35 active cases and 54 break cases based on this criterion. Most of the COSMIC refractivity profiles penetrated down to 0.5-km altitude above mean sea level. We used the lowest-altitude NCEP temperature and pressure data as auxiliary information and applied the RT and OS techniques to retrieve temperature, pressure, and water vapor profiles. The results are presented as averages of the active minus the average of break cases (Fig. 9). Both the RT and OS techniques showed very small changes in vertical temperature structure. The RT method shows a relative warming of the atmosphere above 6 km while the COSMIC 1DVAR technique indicates that the relative warming is above ~3.5 km. The RT, OS, and COSMIC 1DVAR relative humidity changes between the active and break phases agree better with the observations. Thus, the COSMIC 1DVAR results for temperature are somewhat inconsistent with the observed statistics, though they agree better with respect to relative humidity changes. Observational results (Bhat et al. 2002) indicate a smaller specific humidity change at lower altitudes compared to midtropospheric altitudes.
However, the RT, OS, and COSMIC 1DVAR techniques appear to indicate larger specific humidity changes near the surface between the active and break phases of the monsoon. Thus, even the COSMIC 1DVAR retrievals of temperature are questionable in the sense that they may not be appropriately capturing the observed temperature change statistics between the active and break phases of the monsoon.

7. Concluding remarks

In this paper, we have discussed an empirical technique that uses refractivity profile and auxiliary data in the form of surface pressure and temperature to retrieve temperature and relative humidity information to a reasonable accuracy. We have demonstrated the technique with a large number of diverse radiosonde-derived refractivity profiles and also verified it with real radio occultation refractivity profiles from COSMIC along with collocated radiosonde data. Our results are in very good agreement with the analyzed values given along with COSMIC-processed data, as well as the O’Sullivan et al. (2000) technique. We also found that the OS technique gives better specific and relative humidity results because of the relatively smaller error in the pressure retrieval compared to the RT method. Both the RT and OS methods appear to be marginally better in retrieving relative humidity compared to COSMIC 1DVAR. The COSMIC 1DVAR pressure retrieval has similar RMSEs compared to OS. We believe the RT and OS methods may be potentially useful in places where upper-air data are sparse, but some surface meteorological measurements are available to get at least analyzed quality specific and relative humidity profiles.

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REFERENCES


