The ROCSAT-3/COSMIC Mission and Applications of GPS Radio Occultation Data to Weather and Climate

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ABSTRACT

The atmospheric limb sounding technique based on the Global Positioning System (GPS) has been shown to be accurate and of very high vertical resolution. The fact that the GPS radio occultation (RO) technique is not affected by clouds or precipitation, has no instrument drift, and requires no calibration makes it ideally suited for climate monitoring and global weather prediction. The Constellation Observing System for Meteorology, Ionosphere, and Climate (ROCSAT-3/COSMIC) mission will be launched in late 2005, and will provide ~2,500 GPS radio occultation soundings per day to support operational weather prediction, climate analysis, and ionospheric research. Other radio occultation missions are expected to coincide with COSMIC promising additional data. In this paper, we provide status overview of the COSMIC mission, describe its science goals, and review selected GPS RO studies that are relevant to weather prediction and climate analysis.

Keywords: Global Positioning System, Radio Occultation, COSMIC, Climate, Weather

1 INTRODUCTION

Atmospheric and ionospheric profiles can be derived by the radio occultation technique. As a signal travels through the atmosphere from a transmitting Global Positioning System (GPS) satellite to a GPS receiver in Low Earth Orbit (LEO), it is retarded and bent. This results in an added phase and Doppler shift (added to the Doppler shift due to clock drift and the relative motion of the two satellites), which can be detected very precisely by the GPS receiver aboard the low-Earth orbiting satellites. The occulted GPS signal traverses the ionosphere and the neutral atmosphere. To determine properties of the neutral atmosphere, the ionospheric effect on the signal must be corrected. This is done by forming a linear combination of the dual frequency GPS observations, which is free of the dispersive ionospheric delay.

Since relative transmitter and receiver velocities can be determined with an accuracy of about 0.1 mm/sec and clock errors can be differenced out it is possible to isolate the Doppler effect due to the atmosphere, the excess Doppler. Signal bending, $\alpha$, as a function of impact parameter, $\alpha$, (see Figure 1) can be computed with high accuracy from the excess Doppler shift observed at the LEO satellite. In the presence of signal multipath the bending angle is computed by so-called radio holographic techniques utilizing the excess phase and amplitude of the received signal (Gorbunov 2002, Jensen 2003). From the basic bending angle vs. impact parameter data, vertical profiles of refractivity as a function of radius, $r$, can be derived. Further analysis converts refractivity to electron density in the ionosphere (Schreiner et al., 1999). In the neutral atmosphere (stratosphere and troposphere), the bending angle-derived refractivity profiles are primarily a function of temperature, pressure, and water vapor (Rocken et al. 1997). Effects due to hydrometeors and other particulates can generally be ignored (Solheim et al., 1999).

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Figure 1. Schematic of radio occultation observation. Retrieved profiles are attributed to the location of the tangent point. During setting occultations the tangent point approaches Earth surface from above, during rising occultations the tangent point rises above Earth. A GPS occultation observed from ~800 km LEO takes about two minutes to decent from ~100 km to the surface and the bending angle $\alpha$ reaches approximately 1 degree near the surface.

The GPS RO sounding technique, making use of highly coherent radio signals from the GPS has many unique characteristics, including: (i) high accuracy, (ii) high vertical resolution, (iii) all weather sounding capability, (iv) independent of radiosonde or other calibration, (v) no instrument drift and (vi) no satellite-to-satellite bias (Rocken et al., 1997; Kursinski et al., 1997; Kuo et al., 2004). These features make it particularly useful for climate monitoring. With the launch of the planned ROCSAT-3/Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) mission in late 2005, approximately 2,500 GPS RO soundings will be collected per day in near-real-time to support operational weather prediction, climate monitoring, and ionospheric research. Anthes et al. (2000) provided many examples on the possible applications COSMIC GPS RO data to meteorology and climate. In this paper, we describe the status of the COSMIC mission and summarize some recent studies on the analysis of GPS RO data from the CHAMP (Wickert et al., 2004) and SAC-C (Hajj et al., 2004) missions that are relevant to weather prediction and climate analysis.

2 OVERVIEW OF THE COSMIC MISSION

COSMIC is a joint mission between Taiwan and the U.S., with the goal to launch six LEO satellites in late 2005.

The 1-meter diameter, 70-kg. micro satellites are presently integrated and tested at the National Space Program Office (NSPO) in Taiwan. Figure 2 shows one of the first satellites (left panel). All six satellites will be stacked on top of each other and launched at once (Figure 2 right panel).

Figure 2. Assembled COSMIC satellite (left panel) and 6-satellite stack similar to the way it will be launched (right panel).
After the launch vehicle reaches the injection orbit the satellites will be released one by one. The satellites all have propulsion which will then be used to distribute them to their final constellation in 6 orbit planes at 750-800 km altitude, with 72 degree inclination and 24 degree separation. Using propulsion and differential precession it will take approximately 13 months for all the satellites to reach their final destination to complete the constellation. However all satellite will be operational, collecting science data during this deployment phase. In fact the deployment phase provides opportunities for special studies for atmospheric and solid Earth science. Satellites will initially be clustered more densely and their data can be used to study the effect of densely spaced radio occultation profiles on weather models. While the satellites orbit are in close proximity small differences in their relative orbit trajectories will be used by geodesists for studies of Earth’s gravitational filed.

Each COSMIC satellite will carry an advanced GPS RO receiver, a tiny ionospheric photometer (TIP), and a tri-band beacon (TBB) transmitter. Both TIP will and TBB are payloads for ionospheric science and space weather monitoring. The TIP will measure the ultraviolet emission due to the recombination of Oxygen ions and electrons on the night side ionosphere. The intensity of this emission can be related to total electron content (TEC) in TIP’s near-nadir pointing direction. The TBB will transmit on three frequencies (at 150, 400 and 1000 MHz) that can be received on the ground or by other satellites to determine the TEC and ionospheric scintillation levels.

Data from the GPS receiver will be used for neutral atmospheric, ionospheric, and geodetic studies. With the ability of performing both rising and setting occultations as described in Figure 1, COSMIC is expected to produce approximately 2,500 GPS RO soundings uniformly distributed around the globe within a 24-h period (Figure 3).

![Occultation Locations for COSMIC (6 S/C, 3 planes) and EQUARS, 24 Hrs](image)

Figure 3 Typical GPS RO sounding locations from COSMIC (in green) and radiosonde sites in red. The figure also shows, in blue, the expected sounding locations from the Brazilian EQUARS mission. EQUARS is expected to overlap at least with part of the COSMIC mission and would nicely complement COSMIC in the tropics.

### 2.1 COSMIC Data Analysis

One key objective of the COSMIC mission is to demonstrate the value of the RO data for weather forecasting. For this demonstration COSMIC data products will be delivered to the leading numerical weather prediction centers worldwide within less than 180 minutes of data collection on orbit.

To achieve this low-latency goal each satellite will dump its data after each orbit to one of the two high latitude dedicated COSMIC Earth stations in Kiruna, Sweden and Fairbanks, Alaska. These ground stations are currently installed and they will receive the ~9 Mbyte science data dump from each satellite pass. There will be 14-15 passes per day per satellite. The data from each of these dumps is expected to contain ~30 RO soundings, plus all the other GPS
observations, spacecraft data needed for the science data inversion (such as attitude information), and data from the Tiny Ionospheric Photometer (TIP) science instrument.

Since the COSMIC orbit period is 100 minutes the oldest data will be 100 minutes when received on the ground. The data will be forwarded within about 5 minutes to the COSMIC Data Analysis and Archival Center (CDAAC), in Boulder Colorado, and to the Taiwan Analysis Center for COSMIC (TACC) in Taiwan. The CDAAC will also collect data from a worldwide network of ground-based GPS receivers operated by various organizations under the umbrella of the International GPS Service (IGS, http://igscb.jpl.nasa.gov). The ground-based data are needed for the determination of the precise orbits of the COSMIC LEO satellites and for solving for the GPS receiver and transmitter oscillator/clock offsets and drifts. The global GPS data have to be dual frequency observations at a 1Hz sampling rate from high quality GPS receivers. They should be available at CDAAC with no more than a 15 minute delay.

The COSMIC satellite raw GPS data consist of dual frequency phase and amplitude collected at a 1-sec sampling rate from up to 9 satellites in view from the COSMIC satellites. These 1-sec data will be used for orbit determination and for ionospheric studies. In addition there will be 50-Hz observations of GPS phase and amplitude data during rising and setting occultations when the tangent point of the ray from the GPS satellite is between ~120 km altitude and the Earth’s surface. Depending on the geometry of the occultation they last on average about 2 minutes, and for vertical occultations the tangent point descends (during setting occultations) and ascends (during rising occultations) at a rate of ~3km/sec at 100 km height and at a much slower rate of ~ 150 meters/sec near the surface. The slowing of the tangent point descent or ascend rate toward the surface is caused by an increase of the signal bending, and it results in increased vertical resolution of the RO sounding near the surface.

Processing the data involves several steps that are summarized in Figure 4.

![Diagram](image)

Figure 4, summarizes the main steps of RO data analysis for weather and climate research at the COSMIC Data Analysis and Archival Center (CDAAC). The observations (after removal of satellite geometry and clock effects) are excess phase data $s_i$ (i=1,2 for the L1 and L2 GPS frequencies) and $a_i$ the corresponding signal amplitudes. $\alpha_i$ are the bending angles that are computed from $s_i$ and $a_i$ by radio holographic methods in the case of multi path propagation in the lower troposphere, or just from $s_i$ in the case of single path propagation. The dual L1 and L2 bending angles $\alpha_i$ are combined to obtain the ionospheric free bending angle $\alpha$. Using climatology for error suppression and initialization of the bending angles at high altitudes, and the Abel inversion, profiles of refractivity $N$ are computed. Finally under consideration of auxiliary meteorological data (typically from numerical weather models) profiles of temperature, humidity and pressure can be determined.
After the COSMIC raw data have been received at the CDAAC the first processing step involves the computation of precise LEO orbits. CDAAC is planning to use IGS-provided ultra-rapid (IGU) GPS satellite orbits for processing of the real-time data. These orbits are predictions of GPS satellite positions in time. The IGU orbits for COSMIC will be 6-hour predictions. The 3D position errors of these predicted orbits will be better than 0.2 m rms and thus good enough for CDAAC to meet its precision orbit determination (POD) goal of 0.1 mm/sec in velocity. The 0.1 mm/sec velocity error for the COSMIC satellite orbits is based on simulations where we added a Doppler error due to a known satellite velocity error and determined the effect on the retrieved refractivity. The effect of the orbit error increases with altitude because the signal to noise ratio for radio occultations (where the Doppler due to atmospheric effects is the signal and the Doppler due to satellite velocity errors is the noise) decreases exponentially.

![Fractional Refractivity Error due to LEO Velocity Error](image)

**Figure 5.** The effect of satellite velocity errors, projected on the line of sight vector connecting the COSMIC LEO with the occulting GPS satellite. The effect is plotted in fractional refractivity error. It can be seen that if precise orbit determination can keep the satellite velocity error below 0.1 mm/sec its effect will be complete negligible up to 40 km.

Bending angles as functions of impact parameter are obtained for both L1 and L2 GPS carrier frequencies under the assumption of local spherical symmetry of refractivity around the occultation (ray tangent) point (by using Snell’s law). In the upper troposphere where commonly there is no multipath propagation, the bending angles are computed from the excess Doppler. In the lower troposphere, especially in humid regions, atmospheric multipath propagation is common requiring radio holographic processing techniques to obtain the bending angles. CDAAC inversion software uses the so-called Full Spectrum Inversion (FSI) which currently is the fastest and most accurate radio holographic method for close-to-circular orbits. The FSI is applied to the L1 RO signal, while L2 is not used under multipath conditions due to poor data quality (very high noise level and tracking errors). The Doppler-derived L1 bending angle is connected to the radio holographic bending angle at height, which is determined for each occultation individually.

The Doppler-derived bending angles at both GPS frequencies are then combined for the same impact parameter to remove the ionospheric effect (Vorob’ev and Krasil’nikova 1994). Below the height where L2 signals become unusable (typically, 5-10 km) the difference of the Doppler-derived L1 and L2 bending angles is extrapolated and used for the ionospheric correction of the radio holographic L1 bending angle. This results in some error, but not significant since in the troposphere the neutral atmospheric signal is much larger than the ionospheric signal. However, in the stratosphere, the effect of small-scale ionospheric irregularities, which manifests itself as the residual fluctuation of the bending angle after the ionospheric calibration, is the dominant error source. The magnitude of this fluctuation (noise) is substantially different for different occultations and, in most cases, overshadows the effect of thermal noise and residual velocity error.

The effect of noise on the RO refractivity, retrieved with the Abel inversion (see below) especially at higher altitudes depends on specifics of the data analysis. In our analysis we optimize the bending angles by a climate model to minimize the error propagation downward after the Abel inversion. Instead of substituting bending (or Doppler) from a
climate model for observational data above some altitude, we apply statistical optimization of bending angles resulting in weighting of their observed deviation from mean climate according to the ratio of the RMS magnitude of noise to the expected RMS magnitude of weather induced variations of bending angles. Thus statistical optimization results in smooth transition from observations at low altitudes to the mean climate at high altitudes. It provides the most likely vector instead of the observational vector thus resulting in minimizing the error propagation downward when applying Abel inversion in the subsequent step.

Statistical optimization has important implications for the use of COSMIC RO data in weather and climate research. The relative weighting of the observations depends on the noise level of an occultation. For occultations with very high level of noise the weighting of climatology can have significant impact on the retrieved atmospheric profiles as low as 25 km in altitude. For low noise and more typical occultations the climatology has no significant effect below ~45 km. Therefore it is important to take the noise level affecting the occultation data into account when using RO data for weather forecasting and even more importantly for climate monitoring. In CDAAC inversion software the noise level is estimated individually for each occultation based on data collected between 60 and 80 km altitude (where neutral atmospheric signal is negligible compared to noise) and used for calculation of the weighting function for that occultation.

The optimized bending angle is subject to the Abel inversion (Kursinski et al. 1997) to compute a profile of the atmospheric refractivity. The refractivity is a well-known function of the atmospheric pressure temperature and humidity. Under consideration of auxiliary atmospheric information like temperature fields from numerical weather models it is possible to compute profiles of pressure temperature and humidity from the refractivity.

3 EVALUATION OF THE ACCURACY OF RADIO OCCULTATION PROFILES

3.1 Comparison to numerical models

In preparation for the COSMIC mission the CDAAC is processing data from historic (GPS/MET) and present CHAMP and SAC-C satellite missions. To evaluate the RO profiles they can be compared with correlative data and with weather models. For comparison with models the model is interpolated in time and space to the RO sounding.

Figure 6 shows such a comparison for all profiles processed during December 2001 from the CHAMP and SAC-C missions. Approximately 6500 profiles were included in the global statistics. The figure summarizes some important aspects of RO profiles. (1) Agreement with the models between 500 –20 hPa (~5-25 km height) is ~1% in standard deviation with small bias in all three latitude bands that are compared. (2) Tropical RO profiles agree generally worse (larger standard deviation and larger bias) with the models, especially in the lower troposphere. The existence of the negative refractivity bias was first noticed and discussed by Rocken et al. (1997) for GPS/MET, and recently confirmed to be caused by modeling receiver tracking loops (Ao et al., 2003, Beyerle et al., 2003) and suppeerrefraction (Sokolovskiy, 2003). It is anticipated that with the use of advanced signal tracking techniques (open-loop tracking) in future missions, such as COSMIC, such negative bias will be mostly removed. The larger standard deviation in the lower troposphere tropics is due in part to tracking errors and due to in part to larger errors in the model-determined distribution of tropical water vapor. (3) It can also be seen that lower tropospheric retrievals in the northern hemisphere agree better with the models than in the southern hemisphere. This is in part due to the fact that it is winter in the north which results in a drier atmosphere there. In part this also reflects better performance of the models in the data-rich north than in the data-sparse south. It is not yet fully understood why there is worse agreement at 10 mb between RO and the models in the north than in the south. A possible explanation is the high variability of the polar winter upper stratosphere. This variability may be not well reproduced by atmospheric models on one side and result in larger retrieval errors of RO due to optimization by use of a climatology with errors on the other side.
We also compared the RO retrieval to the ECMF models in data rich and in data poor regions. For the same latitude band. Because there is no reason to believe that the RO data are any different between data poor and data rich region this test allows demonstrating that both models perform better in data rich regions than in data poor regions (Figure 7).

Similar results were reported for GPS/MET by Rocken et al. (1997) and they are one of the reasons why RO data are expected to improve models in data poor regions.
3.2 Evaluation of the accuracy of radiosonde data

Balloon soundings from the global radiosonde network, which has been in existence for over 50 years, have been the backbone for operational forecasting and a key data source for climate analysis. Because of its reliability and known accuracy, radiosonde observations have been used as a benchmark to calibrate satellite remote sensing observations and sounding retrievals. The underlying assumption is that the radiosonde observations are, in general, of higher accuracy than the satellite soundings. While this assumption may be valid for passive infrared and microwave sounders, which have relatively low vertical resolution, it is not necessarily true for GPS RO soundings, which are derived from an active sounding technique and have high vertical resolution.

Figure 8 shows the operational radiosonde network. Globally, there are roughly 850 radiosonde stations using about fourteen different types of radiosonde systems. All radiosonde systems have observational errors that are fairly well known, and are dependent upon the type of radiosonde. Moreover, equipment and procedural changes are introduced from time to time. Such changes can introduce spurious climate change signals.

Given the fact that the quality of GPS RO soundings is independent of geographical areas, one may ask the question: Are GPS RO soundings of sufficiently high accuracy to differentiate the performance of different types of radiosonde systems? To answer this question, we calculate the mean absolute difference in refractivity between CHAMP RO data and radiosonde soundings ($N_{CR}$) from June 2001 to March 2004, from 5 km to 25 km in elevation, over five countries that only make use of one uniform type of radiosonde system. We also calculate the difference between refractivities from CHAMP and the European Centre for Medium Range Forecasts (ECMWF) global analysis ($N_{CE}$) over the same geographical area over the same period.

The results (Table 1) show that the Vaisala system and the Shanghai radiosonde system used by Australia and China have the best agreement with the CHAMP RO data. The mean absolute differences, compared with CHAMP RO data, are only 0.18% and 0.19% for Vaisala and Shanghai systems, respectively. The IM-MK3 system used by India has the largest disagreement (0.82%) with the CHAMP GPS RO data. The corresponding differences between the ECMWF...
analysis and RO soundings are smaller than the differences between RO and any of the radiosondes. It is interesting to note that the variation in mean absolute differences between CHAMP and ECMWF does not vary significantly from one region to another (from 0.0.09% to 0.15%), while the CHAMP and radiosonde differences vary by a factor of 4.5 (from 0.18% to 0.82%).

In order to gain further insight on these results, we show in the left panel of Figure 9 the profile comparisons of RO soundings with radiosonde over India. Large deviations exist below 5 km, which reach ~4% near the surface. This is attributed to the well-known negative refractivity bias associated RO soundings in the tropical lower troposphere (Rocken et al., 1997), as a similar bias can be found in the RO and ECMWF comparison (not shown). Above 5 km, however, two large differences are found, one at 8 km, and the other at about 20 km, with maximum fractional differences of 2% (~5K) and 3% (~7.5K), respectively. Moreover, the standard deviations (S.D.) of these differences are large, varying from 1 to 5% (with a mean S.D. of 3.2%). The number of matches (indicated by blue curves) drops significantly above 15 km, which is due to the early termination of the radiosonde soundings. Figure 9 (right panel) shows the corresponding plots over Australia. The differences (both in terms of the mean and S.D.) between GPS RO and radiosondes are much smaller over Australia. The negative refractivity bias of RO soundings below 3 km is also evident, but the magnitude is less. This is attributed to the fact that India is located mostly over tropical latitudes with ample moisture in the lower troposphere. Australia, on the other hand, is located at higher latitudes and has less moisture in the lower troposphere. In the layer between 5 and 25 km, the RO – ECMWF comparison over Australia is comparable to that over India (see Table 1). This again indicates that the quality of RO soundings do not vary significantly between different geographical areas. The large variations of RO – radiosonde deviations between different geographical areas can be attributed to the different performance of different types of radiosonde.

<table>
<thead>
<tr>
<th>Region</th>
<th>Sonde type</th>
<th># of matches</th>
<th>$\Delta N_{CR}$/S.D. (%)</th>
<th>$\Delta N_{CE}$/S.D. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>IM-MK3</td>
<td>87</td>
<td>0.82/3.2</td>
<td>0.15/1.0</td>
</tr>
<tr>
<td>Russia</td>
<td>Mars</td>
<td>1003</td>
<td>0.30/1.3</td>
<td>0.09/0.9</td>
</tr>
<tr>
<td>Japan</td>
<td>MEISEI</td>
<td>107</td>
<td>0.26/1.7</td>
<td>0.14/1.1</td>
</tr>
<tr>
<td>China</td>
<td>Shanghai</td>
<td>402</td>
<td>0.19/1.4</td>
<td>0.15/1.0</td>
</tr>
<tr>
<td>Australia</td>
<td>Vaisala</td>
<td>366</td>
<td>0.18/1.3</td>
<td>0.13/0.9</td>
</tr>
</tbody>
</table>

Table 1. Mean fractional differences and standard deviation (S.D.) of refractivity between CHAMP RO soundings and the soundings from five different types of radiosonde systems. The number of matches is computed as the average number of “CR” matches from 5 to 25 km.

Figure 9. Comparisons of GPS RO and radiosonde over (left panel) India and (right panel) Australia regions. The red curves are mean differences, the green curves are standard deviations, and the blue curves are the data counts (label at the top of figure).
These results suggest that the GPS RO soundings are of high enough accuracy to differentiate the performance among the various radiosonde types. The differences in performance among different radiosondes present a challenge for climate analysis. In this regard, RO is a considerably more robust measurement technique for climate monitoring. Also, as reflected by the close agreement between RO and ECMWF refractivities, the RO observations are more representative of global model values, which are volume averages rather than point measurements.

3.3 Evaluation of Global Reanalysis

Weather prediction models and data assimilation systems have evolved and improved steadily over the past fifty years. This is also true for the global observing system. As a result, the quality of operational global analyses has improved over the years. These improvements are obviously advantageous for operational numerical weather prediction. However, the significant differences over time in the quality of operational global analysis makes them problematic for analysis of climate change or variability. One problem is that the variations in the models and data assimilation systems can introduce fictitious climate change signals. In order to produce a consistent dataset suitable for climate analysis, global reanalyses using a stable and state-of-the-art data assimilation system were produced by a few operational centers. The NCEP/NCAR reanalysis project uses a global analysis/forecast system to perform data assimilation using historical observations, spanning the time period from 1948 to the present (Kalnay et al., 1996). The ECMWF has produced a global reanalysis for the period 1957-2002, including the stratosphere up to 1 hPa, based on the use of variational data assimilation techniques. This is known as the ERA40 reanalysis. Description of the ERA40 can be found at the ECMWF web site (http://www.ecmwf.int). Using a constant data assimilation system, such global reanalyses provide useful information on climate variations. However, before they can be used reliably for climate analysis, it is important to evaluate the accuracy of these reanalyses.

Recently, Randel et al. (2004) compared the deseasonalized interannual variations in tropical tropopause temperatures from various global reanalyses against radiosonde (sparse) observations and GPS RO data (Figure 10). They showed that GPS data agree well with the radiosonde data and the ERA40 reanalysis. However, the NCEP/NCAR reanalysis is an outlier after year 2000. Since the analysis system is constant, this must be related to variations in the input data or how such data are assimilated. For example, the transition from TOVS to ATOVS in July 2001 for the assimilation of the NOAA satellite data may possibly account for such variation. In any event, this comparison shows that the GPS RO data can be a valuable arbitrator for different data sets for global climate analysis.

![Figure 10](Image)  
**Figure 10.** (top) time series of deseasonalized 100 hPa temperature anomalies over 10° N-S, showing results from four different data sets. Each time series is normalized to be zero for April 1995 – February 1997. (bottom) Difference of the respective time series with averaged radiosonde data. (Figure from Randel et al., 2004).
3.4 Evaluation of Operational Analyses

To further illustrate the value of GPS RO data in assessing the quality of global analyses, we compare the GPS RO data from the SAC-C mission with the NCEP operational analysis, the ECMWF operational analysis and the NCEP/NCAR reanalysis over the region south of 40°S for the month of December 2001. The results show that the NCEP and ECMWF operational analyses are of comparable accuracy. The NCEP/NCAR reanalysis is again an outlier. The rms difference in refractivity for the NCEP/NCAR reanalysis is about 0.5% higher than those of the operational analyses throughout the troposphere, and the difference is even larger near the tropopause (Figure 11, left panel). The mean refractivity differences, verified against SAC-C GPS RO data, indicate very small bias from 700 hPa to 150 hPa for the two operational analyses (Figure 11 right panel). However, the NCEP/NCAR reanalysis exhibits a significant positive bias (more than 1% in refractivity) in the layer between 200 to 300 hPa. The right panel of Figure 4 also shows the well-known negative refractivity bias relative to all the global analyses. The negative bias begins at about 700 hPa and reaches ~1% near the surface. These results indicate that GPS RO data (at least for the layer between 5 and 25 km) are valuable for calibrating global operational analyses, and will be an important data source for weather and climate analysis.

![RMS Difference of Refractivity](image)

![Mean refractivity difference](image)

Figure 11. RMS (left panel) and mean differences (right panel) in refractivity between SAC-C GPS RO soundings and the three global analyses: (i) NCEP operational analysis (blue), (ii) ECMWF operational analysis (red), and (iii) NCEP/NCAR reanalysis (green). Vertical axis is pressure in hPa.

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