Assimilation of Global Positioning System Radio Occultation Observations into NCEP’s Global Data Assimilation System

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ABSTRACT

The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission launched six small satellites in April 2006, each carrying a GPS radio occultation (RO) receiver. At final orbit, COSMIC will provide ∼2500–3000 RO soundings per day uniformly distributed around the globe in near–real time. In preparation for the assimilation of COSMIC data in an operational framework, the NCEP/Environmental Modeling Center (EMC) has successfully developed the capability of assimilating profiles of refractivity and bending angle. Each forward operator has been implemented with its own quality control and error characterization. In this paper, the infrastructure developed at NCEP/EMC to assimilate GPS RO observations, including forward models, observational and representativeness errors, and quality control procedures, is described. The advantages of using a forward operator for bending angle versus refractivity are discussed and some preliminary results on the benefits of the GPS RO in weather analysis and forecasts are presented. The different strategies adopted at NCEP/EMC to assimilate GPS RO data are aimed to select the most appropriate forward operator in the operational data assimilation system when COSMIC products are stable and routinely available to the Numerical Weather Centers. In the meantime, data from the Challenging Minisatellite Payload (CHAMP) satellite is available in non–real time and has been used in the assimilation tests to examine the potential benefits of the GPS RO–derived products. In the preliminary results presented in this study, the use of GPS RO observations slightly improves anomaly correlation scores for temperature (by ∼0.01–0.03) in the Southern Hemisphere and Tropics throughout the depth of the atmosphere while a slight degradation is found in the upper troposphere and stratosphere in the Northern Hemisphere. However, significant reduction of the temperature and humidity biases is found for all latitudes. The benefits from assimilating GPS RO data also extend to other fields, such as 500-hPa geopotential heights and tropical winds, demonstrating the potential use of GPS RO data in operational forecasting.

1. Introduction

Global positioning system (GPS) radio occultation (RO) data are provided by receivers on board the low-earth-orbiting (LEO) satellites (Ware at al. 1996). As the radio signals transmitted by the GPS satellites pass through the atmosphere, they are refracted because of the density gradients along the path. As an LEO satellite sets or rises behind the earth’s limb relative to the GPS transmitter satellite, the onboard GPS receiver takes measurements of the phase and amplitude of the L1 (∼19 cm) and L2 (∼24.4 cm) GPS signals. These phase measurements are the relevant fundamental ob-
servables and, together with the precise knowledge of the positions and velocities of the GPS and LEO satellites, can be collectively used to derive the inferred atmospheric bending angle as a function of the asymptote miss distance (or “impact parameter”) for each signal under the assumption of spherical symmetry. (The impact parameter is the quantity \( a \) shown in the idealized geometry depicted in Fig. 1.)

The contribution of the ionosphere to the bending can be largely removed by using the first-order relationship between the ionospheric refractivity index and the frequency of the signal, and the geometric separation of both rays (L1 and L2) due to the dispersive nature of the ionosphere at the GPS frequencies (Vorob’ev and Krasil’nikova 1994). This is done by deriving a linear combination of the bending angle as a function of the impact parameter for the L1 and L2 signals. However, the noise introduced by this ionospheric-compensated linear combination becomes comparable to the signal of the neutral atmosphere above a height of \( \sim 40-90 \) km, depending on the conditions of the ionosphere (Hajj et al. 2002). The residual ionospheric noise represents the main source of error for the bending angle in the upper stratosphere.

Under the assumption of local spherical symmetry and the use of climatology information, refractivity profiles at the ray perigee point can be derived from bending angle profiles through Abel transform inversions (Hajj et al. 2002, 1994; Kuo et al. 2004). The use of climatology at altitudes above \( \sim 40 \) km reduces the propagation of the ionospheric noise present in the inferred profiles of ionospheric-compensated bending angle (significant above heights \( \sim 40-90 \) km) to lower altitudes when using an Abel inversion to reconstruct the refractivity structure. It is important to note that the assumption of spherical symmetry is used in the retrieval of bending angles and refractivities from the GPS measurements and can potentially damage the impact of GPS RO in data assimilation.

Because of the high accuracy of the RO observations (Kursinski et al. 1996; Rocken et al. 1997), it is expected that GPS RO data might have a significant impact on operational weather analyses and forecasts. Previous studies have shown the potential of GPS RO data in numerical weather prediction (NWP; Liu et al. 2001; Poli and Joiner 2003; Zou et al. 2004, Wei and Kuo 2004; Cucurull et al. 2006). However, these studies did not assimilate other satellite observations currently available in operations and made use of older versions of meteorological models that clearly limit their findings. Healy et al. (2005) found significant reduction of the errors of the temperature fields in the upper troposphere and lower stratosphere when profiles of refractivity were assimilated into the Met Office NWP system. More recently, the assimilation of derived soundings of bending angle has been proven to have a positive impact at the European Centre for Medium-Range Weather Forecasts (ECMWF; Healy and Thépaut 2006). These authors found a reduction in forecast errors in the stratosphere over the Southern Hemisphere and at 100 hPa in the Tropics, but they needed to switch off the surface pressure increments due to the RO observations in the analysis in order to not degrade the prediction of 500-hPa geopotential heights (500Z). Furthermore, observations below 5 km were not considered for assimilation in the study, thus limiting the possibility of GPS RO data directly improving the humidity and temperature fields in the lower troposphere.

The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission launched six small satellites in April 2006 (Anthes et al. 2000), each carrying a GPS occultation receiver. The COSMIC constellation will provide \( \sim 2500-3000 \) RO soundings per day, nearly uniformly distributed around the globe in near–real time (less than 180 min) when the satellites reach their final orbit configuration (\( \sim 800 \) km). GPS RO data are minimally affected by aerosols, clouds, or precipitation, are independent of radiosonde calibration, and are not expected to have instrument drift and satellite-to-satellite instrument bias. All these factors make the GPS RO observations attractive to the NWP community. GPS technology is a limb-sounding...
geography complementary to ground and space nadir-viewing instruments, characterized by high vertical resolution and lower horizontal resolution (Fig. 1). We should note that at the time this paper was written the COSMIC RO data was not yet available.

The National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) is planning to assimilate GPS RO observations from the COSMIC mission (and other future GPS RO satellites) into its next-generation National Centers for Environmental Prediction (NCEP) Global Data Assimilation System. The assimilation of the GPS RO data requires the development of an appropriate forward model, the adjoint of the forward model, appropriate observational and representativeness error estimates, quality control procedures, data handling routines, and data monitoring software. In preparation for the use of COSMIC data, the NCEP/Environmental Modeling Center (EMC) has developed the capability to assimilate soundings of (ionospheric compensated) bending angle and derived refractivity profiles. A priori-derived profiles of bending angle are preferred for assimilation because they are less processed data and are not weighted with climatology. However, as soundings of bending angle are less smooth in the vertical than refractivities and they might contain residual ionospheric noise at higher altitudes, its assimilation in a NWP model is more challenging.

Ionospheric-compensated bending angles and profiles of refractivity appear to be the most suitable types of GPS RO observations for data assimilation. The assimilation of less processed retrievals would require very complex forward operators. For instance, if there is not postprocessing on the raw phase delays and amplitudes, the precise knowledge of the GPS and LEO orbits and an ionospheric model would be necessary to assimilate the data. In the presence of multipath reception (i.e., several rays arrive at the receiver at the same time), the forward operator should additionally include a wave propagation model. The bending angles derived from the two GPS frequencies, including the contribution of the ionosphere, would still require the modeling of the ionospheric effects in the data assimilation system (Kuo et al. 2000).

In this paper, we describe the strategies adopted at NCEP/EMC to get ready for the use of GPS RO observations in an operational framework. We also present some preliminary results from the GPS RO Challenging Minisatellite Payload (CHAMP) mission (Wickert et al. 2001). In these early experiments, benefits of the assimilation of soundings of bending angle are compared with the assimilation of refractivity profiles. The forward operator for each type of observation is tuned with its corresponding quality control procedures and errors structure. We should also remark that both forward models are treated as local operators, that is, the effects of horizontal refractivity gradients have been neglected in the design of the forward model.

Future work at NCEP/EMC will include the evaluation of possible benefits when the horizontal gradients are taken into account.

Our goals here are 1) to demonstrate that NCEP/EMC has developed the capability to use GPS RO observations in its data assimilation system and 2) to present preliminary results on assessing the value of the GPS RO observations added to the current conventional and satellite observations in operational global analyses and forecasts. In addition, we analyze the differences between the assimilation of soundings of bending angle and refractivity.

It is important to emphasize that it is, as far as we know, the first time that the same model is used to evaluate the advantages and disadvantages of profiles of bending angle versus refractivity when weighted with the observations currently used in operations. Consequently, this is the first fair comparison between the potential of the GPS RO bending angle and refractivity in a NWP center. However, since it is necessary to apply different quality control and error characterization for refractivity and bending angle, the comparison is not limited to only the type of observation being used.

The structure of the paper is as follows: sections 2 and 3 describe the local forward operators for refractivity and bending angle, respectively. Owing to the unavoidable neglect in the respective forward operators of some physical effects that actually influence the measurements significantly, each operators needs to be characterized by its own pattern of effective measurement errors, and hence its own quality control. The experiment design is presented in section 4. Results for the different experiments are discussed in section 5. Finally, the summary and conclusions are given in section 6.

2. Assimilation of refractivity data

a. Forward operator

When GPS RO observations of refractivity \( N \) as a function of the geometric height \( z \) are being assimilated, the following forward operator is used to map model variables to refractivity space (Smith and Weintraub 1953):

\[
N = 77.6 \left( \frac{P}{T} \right) + 3.73 \times 10^3 \left( \frac{P_v}{T^2} \right).
\]
where $P$ is the total atmospheric pressure (hPa), $T$ is the atmospheric temperature (K), and $P$ is the partial pressure of water vapor (hPa). In most contexts the first term in (1) is considerably larger than the second. The second term becomes important in the troposphere for temperatures higher than 240 K and contributes up to 30% of the total $N$ in the tropical boundary layer.

To evaluate (1), we first compute the geopotential heights of the model levels at the latitude and longitude of each observation. The geometric height of the observation is then converted to geopotential height in order to locate the observation between two vertical levels (the equations used in the conversion can be found online at http://mtp.jpl.nasa.gov/notes/altitude/altitude.html). Then model profiles of pressure, temperature, and water vapor pressure are interpolated to the location of the observation (both in the horizontal and the vertical) to compute the $N$ value. Note that this is a different approach from the one adopted in Healy et al. (2005), where $N$ is directly interpolated from model levels to the location of the observations by assuming an exponential behavior for $N$. Furthermore, in our implementation, the drift of the tangent point of the ray connecting the receiver and transmitter during an occultation is accounted for by treating each measurement from a RO sounding as an independent observation, that is, characterized by its own altitude, latitude, and longitude.

The implementation of the forward operator in (1) passed all the tangent linear and adjoint tests. In the minimization algorithm, surface pressure and model profiles of temperature and humidity are adjusted to fit the observations of $N$. The geopotential heights of the model levels are updated through the increments in model (virtual) temperatures and surface pressure. Consequently, the observations are allowed to change their location in the vertical within the model.

b. Quality control

Two quality control (QC) procedures for the GPS RO data are currently being used in the NCEP/EMC data assimilation system. The first one, a gross check, is standard for the different sets of observations being assimilated into the system. It involves the ratio between the innovation vector (i.e., difference between the observed and forecast values) and the observational error of the data. If this ratio exceeds a certain threshold (in this case 10) then the observation is rejected. This is a very rough check and it is only intended to identify gross outliers.

A second QC check has been implemented for the GPS refractivity data, based on a month’s comparison (July 2005) between CHAMP observations and model analyses without GPS RO being assimilated. Results of this comparison are shown in Fig. 2. The figure shows the mean difference (dark continuous line) and standard deviation (dot--dashed line) as percentages of the differences between observations and model simulations of $N$ as a function of $z$ for the (Fig. 2a) Northern Hemisphere (north of 30°N), (Fig. 2b) Tropics (between 30°N and 30°S), and (Fig. 2c) Southern Hemisphere (south of 30°S). The counts as a function of height are also shown in the figure as a light continuous line. The proportion of RO soundings that penetrate deeper into the lower troposphere is relatively small due mainly to tracking errors caused by strong water vapor gradients in the moist lower troposphere. The tracking errors should be eliminated in the COSMIC GPS RO data by replacing the closed loop tracking of the L1 RO signal with an open loop tracking, which has been implemented by the Jet Propulsion Laboratory in COSMIC receivers (Sokolovskiy 2001). This means that the numbers of COSMIC profiles reaching the lower troposphere will be larger than in the case of CHAMP. Only those profiles qualified as “good” by the processing center (see section 4b) are used to estimate the statistics in Fig. 2, which accounts for a rejection of 3.7% of the data. In the data assimilation system, observations are rejected if their deviation from forecast exceeds three standard deviations as shown in Fig. 2.

Note that a significant negative bias is present in the lower tropical troposphere in Fig. 2b. Tracking errors, noise in the phase and amplitude converted to refractivity through a nonlinear transformation, and superrefraction are the most significant sources of biases in $N$ in the lower troposphere. Superrefraction occurs at the sharp transition at the top of the moist planetary boundary layer and results in a negative bias in $N$ below this layer after an Abel transform inversion. Unfortunately, this error might not be solved by any software improvement (Sokolovskiy 2003). In general, assessing the magnitudes of these biases is difficult and is currently under research (S. Sokolovskiy 2006, personal communication). Other errors in the lower troposphere might include the effects of a nonspherically symmetric atmosphere or effects of neglected horizontal gradients of refractivity, assumed in the processing of the GPS RO. In addition, a possible bias in the analysis might also contribute to the larger biases at lower levels.

From Fig. 2, the variability of the differences is larger at higher altitudes in the Southern Hemisphere (where the observations and the model simulations also show larger variability). The combination of the higher temperature gradients present in the winter hemisphere with the possible lower skill of the global models in
simulating refractivities in the Southern Hemisphere at these high altitudes might be one of the reasons for the larger standard deviations. In general, when compared to other latitudes, the mean differences and standard deviations are larger in the Southern Hemisphere (Fig. 2c) throughout the depth of the atmosphere except within the moist lower troposphere. Since there is no reason to expect latitudinal differences in the quality of

Fig. 2. Mean (dark continuous line) and standard deviation (dot–dashed line) of fractional refractivity differences between GPS RO and model simulations as a function of geometric height for July 2005 for the (a) Northern Hemisphere (north of 30°N), (b) Tropics (between 30°S and 30°N), and (c) Southern Hemisphere (less than 30°S). The counts are shown as a light continuous line.
the GPS RO observations between ~20 and 30 km, provided that only low noise occultations are considered in the polar regions (Kuo et al. 2004), the results from Fig. 2 suggest that GPS RO might improve the model bias more in the Southern Hemisphere.

In the lower troposphere, the larger standard deviations are found in the Tropics (Fig. 2b). However, note that in this case the number of observations rapidly decreases as compared to other latitudes, probably due to tracking errors caused by the complicated structures of \( N \). The variability of the GPS RO observations and simulations of the observed quantities is also larger in the lower tropical troposphere than in other latitudinal ranges, due mainly to multipath and superrefraction effects.

At high altitudes, profiles of \( N \) might also suffer from errors from the climatology model and residual ionospheric noise. Both effects will propagate downward with the use of an Abel transform inversion. As it is not desirable to have observations containing climatology-derived errors or ionospheric noise in a data assimilation system, we have tuned our QC system by rejecting all the data in a profile below an observation that failed the QC. Observational errors provided in Kuo et al. (2004) have been tuned to account for a representativeness error that is characteristic of our model.

3. Assimilation of bending angle data

a. Forward operator

Motivated by the desire to avoid possible errors introduced by the use of climatology in the retrieval of \( N \) we implemented the capability to assimilate soundings of bending angle. The ionospheric-compensated bending angle \( \alpha \) can be expressed as a function of the observed impact parameter \( \alpha \) as follows:

\[
\alpha = -2a \int_0^x \frac{d \ln n}{dx} \left( \frac{x}{x^2 - a^2} \right)^{1/2} \, dx, \tag{2}
\]

where \( n \) is the index of refraction and \( r \) is the radius of a point on the trajectory of the ray. The magnitude \( x \) is the refractional radius (equivalent to the classical angular momentum) and remains constant along the trajectory of a ray for a spherically symmetric atmosphere. The bending angle is usually written in terms of \( x \) rather than \( r \) because, under the assumption of spherical symmetry, the inversion of bending profiles in (2) gives profiles of refractivity \( N = (n - 1)10^6 \) as a function of the geometric height. The singularity on \( a \) can be overcome by evaluating the integral on a new grid \( s \), where

\[
x = \sqrt{a^2 + s^2}. \tag{3}
\]

The integral in (2) is then evaluated in an equally spaced grid in \( s \), so the trapezoidal rule can be easily and accurately applied. By experimentation, we have found that a grid space of 5 km in \( s \) is adequate. The procedure used to evaluate the forward operator in (2) is composed of the following steps:

(i) Model profiles of geopotential heights and \( N \) are computed at the location of the observation. Geopotential heights are then converted to geometric heights \( z \).

(ii) The radius of curvature of the local spherical fit to the ellipsoid near the lowest tangent point of the profile (provided in the observational files, see section 4b) is added to \( z \) to get the radius \( r \).

(iii) Profiles of \( N \) are converted to refractive index profiles, \( n = 1 + 10^{-6}N \).

(iv) Model profiles of refractional radius \( x = nr \) are calculated.

(v) Both \( n \) and \( x \) are extrapolated above the model top (0.266 mb) by assuming an exponential decay for \( N \) within the two uppermost levels.

(vi) Model profiles of \( n \) and \( x \) are interpolated to the new grid \( s \).

(vii) The integrand in (2) is computed on the new grid \( s \).

(viii) The integral is evaluated in an equally spaced grid.

We found that some approximations commonly applied in (2) make the forward model highly nonlinear when evaluating the integral in the new grid \( s \). For instance, if we assume an exponential behavior for \( N \) within a model layer, as adopted in Healy et Thépaut (2006), its derivative is highly discontinuous because of the fact that the model levels are not equally spaced. As a consequence, the integral in (2) is highly nonlinear with respect to perturbations in model variables, with larger nonlinearities for observations located within lower levels. To overcome this problem, we make use of a carefully constructed interpolator that preserves continuity not just of values, but of interpolated gradients, across intervals. This is accomplished by centering Lagrange polynomials (Abramowitz and Stegun 1970) of some chosen even degree (such as quadratic) at each grid point, but averaging the proximate pair of them within any grid interval with weights that linearly partition unity across the extent of the grid interval. The continuity of gradients ensures sufficient continuity of the forward model and its derivatives with respect to perturbations of model variables. Values for the soundings of \( N \) and their derivatives are computed in the new
grid $s$ from their model counterpart values in $x$. As in the case of $N$, the procedure described above to compute $\alpha$ successfully passed the tangent linear and adjoint tests.

From a statistical point of view, we obtain the same results as in Healy et Thépaut (2006), our procedure should be faster (we do not make use of the error function) and we do solve the integral more accurately. In addition, and as in the case of $N$, we take into account the horizontal shifting of the tangent point with height (i.e., each ray has a different latitude and longitude of the tangent point). The differences from assuming fixed coordinates of the tangent point might become significant at higher altitudes (Poli and Joiner 2004).

b. Quality control

The QC applied to $\alpha$ is similar to the one used for $N$: a gross check rejects observations with large normalized innovation vectors ($>10$); then a statistical QC rejects observations that deviate more than three standard deviation units from the background, based on a month comparison (July 2005) between observations and model simulations of $\alpha$. The only significant difference with $N$ is that, for bending angle, if one observation in a profile fails the QC we reject all the observations below only in the case that its impact height (defined as the difference between $\alpha$ and the radius of curvature of the profile) is lower than 10 km. The reason for this is that residual ionospheric errors present at high altitudes are not propagated to lower altitudes in the case of $\alpha$. At lower heights, we reject observations because noise, horizontal refractivity gradients, and tracking errors might degrade the quality of the observations, as in the case of $N$.

Figure 3 shows the mean difference and standard deviation (in percentages) of the differences between the observations of $\alpha$ and their model counterpart for the same period used in the case of $N$ as a function of the impact height. As in section 2, only observations flagged as good by the processing center have been used in the comparison. When compared to Fig. 2 it is apparent that the soundings of $\alpha$ show a larger variability than the corresponding $N$ profiles, which did not exceed a fractional difference of 5%. The plot also shows a slight reduction of the stratospheric bias in the Southern Hemisphere as compared to Fig. 2. However, negative biases in the lower troposphere remain. As was the case with $N$, Fig. 3 indicates the potential of GPS RO bending angles to improve the bias of the model in the Southern Hemisphere between $\sim$20 and 30 km.

We cannot explain why the biases in the lower troposphere in Fig. 3 are in general slightly larger than the ones found in Fig. 2. The main source of the differences between the biases in $\alpha$ and $N$ is superrefraction. However, current studies with open loop tracking of the L1 RO signal do not show significant differences in the fractional bias between both types of observations, which might suggest that the contribution of superrefraction to the bias is statistically less significant than that of the noise (S. Sokolovskiy 2006, personal communication). Neither is there an obvious reason to explain why the tracking errors would result in larger biases in $\alpha$ than in $N$. One possibility is that the bias might be related to the model. The fact that the number of counts is largely reduced below an impact height of around $\sim$7 km could also give less statistical meaning to the results at these lower altitudes. On the other hand, since the Abel inversion transform is a low-pass filter, we would expect fractionally smaller tracking errors in the case of $N$ than $\alpha$, which would explain the larger standard deviations found in the lower troposphere in Fig. 3.

In general, representativeness errors are also expected to be larger when simulating $\alpha$. This is because of the higher vertical variability of the observations of $\alpha$ as compared to the smoothed profiles of $N$. In particular, we found that at higher altitudes in the Northern Hemisphere and the Tropics the variability of the differences between observations and model simulations of $\alpha$ were not much different from the variability of the observations themselves.

The GPS RO soundings provided by UCAR in the Binary Universal Format for data Representation (BUFR) format (see section 4b) have an equally spaced grid in the case of $N$ but the grid distance decreases with height for the bending angles. As we computed the statistics on a 1-km vertical grid, this explains why the counts do not decrease with decreasing height in Fig. 3.

We have tuned the errors provided in Healy and Thépaut (2006) to characterize the error structure associated with the soundings of $\alpha$. This error decreases linearly from 10% at the surface to 1% at an impact height of 10 km. Above this altitude, the maximum value between 1% of the observed value and 7 micro-radians is used.

4. Experiment design

a. Data assimilation system

A prototype version of the Grid-point Statistical Interpolation (GSI) analysis code coupled with the Global Forecast System (GFS) is used to conduct the impact experiment studies (Wu et al. 2002). The GSI is developed by NCEP/EMC and is supported for the community by the Joint Center for Satellite Data As-
The GSI replaced the current operational NCEP Spectral Statistical Interpolation (SSI) global analysis system (Derber et al. 1991) and regional data assimilation system in May 2007. The main difference with respect to the SSI is that it replaces the spectral definition for background errors with a grid point definition based on recursive filters that permits more degrees of freedom in defining the error statistics adaptively.

The GSI system is a three-dimensional variational algorithm capable of assimilating a wide range of conventional and satellite observations, including the Atmospheric Infrared Sounder (AIRS) radiances. The minimization algorithm is composed of two outer itera-

**Fig. 3.** Same as in Fig. 2, but for the differences of the bending angle.
tions to account for weak nonlinearities in the cost function that are complex to include in the minimization. In the first external iteration the first guess is a 6-h forecast, while in the second one it is the solution from the previous outer iteration.

In each outer loop there are several inner iterations to minimize the cost function. Some nonlinear forward operators (e.g., precipitation) are considered in the inner minimization algorithm. The 3-, 6-, and 9-h forecasts (or the updated forecasts in the second outer iteration), are interpolated to the location and time of the observations to evaluate the cost function. The resulting additional increment at the end of the second outer loop is added to the previously updated 3-, 6-, and 9-h forecasts. The analysis is the resulting updated 6-h field. In the inner loop, the current solution is iteratively updated by using a nonlinear conjugate gradient algorithm, which attempts to find the solution that minimizes the cost function. (A detailed description of the GSI code is available online at http://wwwt.emc.ncep.noaa.gov/gmb/treadon/gsi.)

b. GPS RO observations

Soundings of $N$ and $\alpha$ from the CHAMP mission are available in the BUFR format (WMO 1994) from the University Corporation for Atmospheric Research/COSMIC Data Analysis and Archive Center (UCAR/CDAAC) Web site (online at www.cosmic.ucar.edu). In preparation for the operational assimilation of COSMIC observations, the CHAMP RO observations are routinely pushed from UCAR to the NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) server and then stored at NCEP in order to be used for study cases. Even though CHAMP data is not received in real time, this routine has been established in order to test the end-to-end data flow of the GPS RO data.

The BUFR files provide soundings of $\alpha$ as a function of $a$, profiles of $N$ as a function of $z$, and other derived atmospheric parameters as a function of the geopotential height. The vertical resolution is 200 levels and $z$ ranges between 0 and 6 km or higher at the bottom to around 40 km at the top. UCAR/CDAAC does not provide data at higher altitudes than around 40 km because of the heavy weight of residual ionospheric noise in the case of $\alpha$ and of climatology in the case of $N$. Values of latitude; longitude; $\alpha$, $a$, and $N$ are then interpolated to these 200 evenly spaced levels. The files also contain additional information related to the geometry of the radio occultation.

In the BUFR files, information on the latitude and longitude of the observations are only contained in the $N$ section. However, these coordinates are also necessary when assimilating soundings of $\alpha$ in order to locate the observations in the model grid. As a consequence, UCAR/CDAAC BUFR soundings of $\alpha$ are specified at the same latitude and longitude as the $N$ profiles. Because of the fact that there is a nonlinear relation between $x$ and $x$ in (3) or, in other words, between the radius of tangent point and $a$ (Fig. 1), and in order to preserve a mapping of $a$ heights to $z$ heights, the vertical resolution of profiles of $\alpha$ increases when decreasing height, given a constant spacing in $z$ for the geometric case.

The fact that soundings of $N$ and $\alpha$ are specified at 200 levels in the vertical and GSI/GFS has a lower resolution of 64 levels might introduce some aliasing effects. To help prevent such a situation, we applied some filtering to the profiles by increasing the errors of the observations within the same model layer and thus reducing their effective weight in the cost function. These errors were increased proportionally to the square root of the number of observations within the layer.

5. Results

a. Performance of the assimilation algorithm

To evaluate the performance of the algorithm when analyzing observations of $N$ and $\alpha$, we assimilated GPS RO data for a single analysis case. No other observations were assimilated in this particular analysis, as our focus was to evaluate the behavior of the assimilation algorithm. We used the same resolution as used in operations, with a horizontal resolution of T382 (~35 km on a Gaussian grid) and 64 levels in the vertical, ranging from the surface to around 0.27 hPa.

Figure 4 shows the performance of the assimilation of profiles of $N$ for 0000 UTC 12 July 2005. A total of 46 profiles were available for this period. Figures 4a-c show the percentage differences between the observations and model simulations of $N$ at the beginning of the first outer iteration (or the fit to the first guess), at the beginning of second outer iteration, and for the final analysis, respectively. All figures show data plotted as functions of $z$ and observations that passed (dots) and got rejected (diamonds) by the QC described in section 2 are also indicated. In an assimilation context, Fig. 4a shows the innovation vector while the residuals of the analysis are shown in Fig. 4c. From the figures, it is evident that some observations rejected in the first outer iteration are kept in a later loop. This is because as the model fits the observations better, other observations rejected in an earlier step get closer to the cur-
rent solution and are incorporated in the assimilation algorithm. The fact that the model and observations get closer at each iteration shows the good performance of the minimization algorithm.

In this particular case, the amount of data rejected by the QC decreases from 2.78% at the beginning of the first outer iteration to 1.4% at the end of the minimization, where all the data discarded by the QC belong to the same profile, located in the Southern Hemisphere.

The same GPS RO profiles, but now using soundings of $H^{9251}$, were assimilated in a second analysis experiment.
by using the forward operator described in section 3. Results are presented in Fig. 5. As seen in the $N$ analysis case, the differences between the GPS observations and their model counterpart get smaller at each iteration and some observations rejected in the first place are later assimilated. As expected from Figs. 2 and 3, the differences are in general larger when dealing with $\alpha$ than $N$. Remember that the use of an Abel transform inversion to retrieve $N$ profiles smooths the data and consequently reduces the representativeness error of the model.

As the QC is less restrictive in the case of $\alpha$ (see section 3), the amount of data being rejected during the assimilation procedure is also lower as compared to the $N$ analysis case (Fig. 4). When assimilating observations of $\alpha$, the number of observations rejected by the QC decreases from 0.5% to 0.2% during the minimization. It is important to note that even if the amount of data rejected is lower in the case of $\alpha$, the observations are now sparser among the different latitudes.

If observational (including representativeness) errors
are correctly specified, the variance of the normalized
differences between observations and model simula-
tions ranges between ~1 and 2 at the beginning of the
minimization and decreases to ~1 at the end. In our
case study, this ratio is reduced during the minimization
from 1.6 (1.7) to 0.4 (0.6) when soundings of $N$ (\(\alpha\)) are
being assimilated. The fact that we obtain a lower value
than 1.0 might indicate that some errors treated as un-

Fig. 6. Temperature differences for 0000 UTC 12 Jul 2005 at 850 hPa between the assimilation of current observations and GPS
RO profiles of the (a) refractivity and (b) bending angle, and the assimilation of current observations alone.
correlated are indeed correlated. Overall, we found that the total cost function was reduced by around one-half at the end of the minimization. For these experiments, we also found that the contribution of the GPS RO to the total cost function for the analysis, divided by the number of observations was ~0.5. This is consistent with a well-behaved data assimilation system (Bennett et al. 1996).

Fig. 7. Same as in Fig. 6, but at 300 hPa.
b. An analysis case study

Since the impact of the GPS RO data in the context of an operational data assimilation system needs to be evaluated along with the other observations, we conducted a second analysis study where conventional and satellite data were additionally assimilated. We selected the same date as in the previous section, 0000 UTC 12 July 2005, and the same high model resolution, T382L64.

Figures 6a and 7a show the difference between the temperature analysis obtained by assimilating the current observations along with soundings of $N$ and the assimilation of the current observations alone. The differences are represented at 850 (Fig. 6a) and 300 hPa (Fig. 7a). It is quite encouraging to see that GPS RO can have a significant impact in areas covered by large amounts of observations, as is the case for the west coast of North America (Fig. 6a). This can be a result of the profiles of $N$ themselves or an indirect effect of the GPS RO data on the QC of other observations. Significant impact at 300 hPa is also found over the Arctic (see the strong negative difference of $\sim 1.0$ K north of Russia) and over Eastern Greenland with a warm difference of $\sim 0.3$ K (Fig. 7a). Over the oceans, the assimilation of $N$ is cooling down the air over the Southern Indian Ocean (around 0.5 K at 300 hPa) and warming up some areas over the Pacific Ocean, south of Africa ($\sim 0.4$ K at 300 hPa) and the tropical Indian Ocean. The greater impact of GPS RO over seas is to be expected given the relative sparsity of conventional data there.

Results from the same analysis study, but using soundings of $H_925$ rather than $N$ profiles, are shown in Figs. 6b and 7b. It is evident from the figures that the soundings of $\alpha$ are also producing a significant impact even amongst the current available observations. However, it is interesting to note that the structures between Figs. 6a,b and 7a,b are quite different. This indicates that the assimilation of profiles of $N$, by making use of the QC and errors described in section 2, produces results differing from those obtained with the forward operator described in section 3. Both systems in turn can reject different conventional observations, as they will generate different updated solutions at each iteration (see section 4a).

In Fig. 6b, a warm difference ($\sim 0.5$ K) in temperature is apparent near the eastern coast of Greenland at 850 hPa. At 300 hPa (Fig. 7b) this difference has moved inland while a negative difference develops in the eastern coast of Greenland. This was not the case for the assimilation of refractivities, where the strongest warm gradient over Greenland was located inland and was only significant at 300 hPa.

At 300 hPa, both the ingestion of soundings of $\alpha$ and profiles of $N$ show negative differences on temperature over the Arctic, with the larger increments found when $\alpha$ is being assimilated. Structures over the Indian Ocean are present in both cases, with different intensity depending on the area. In contrast, the structures found in Figs. 6a and 7a over the Antarctic have been largely removed in Figs. 6b and 7b. This is because some observations (GPS RO or another type) have been rejected by the QC in one case but not in the other one. Weaker structures are generally found with the assimilation of $\alpha$ over the Pacific Ocean. This is also applicable at 850 hPa, where the stronger warm difference in $\alpha$ is located more to the south than in the $N$ case.

Notice that the increments found over the west coast of North America at 850 hPa are stronger when sound-
nings of $\alpha$ are being assimilated. As the structures are found around the same areas, it seems to indicate that the same profiles produce different structures depending on the GPS RO data type being assimilated and/or the QC of other observations being modified differently.

In summary, the assimilation of GPS RO does not produce a neutral impact when being assimilated along with the current observations used in operations. In addition, the effects of the GPS RO are different if the profiles are assimilated as $N$ or $\alpha$ following the procedures described in sections 2 and 3, respectively. Results are similar at other vertical levels and for other variables.

c. Cycling experiment

To evaluate the full performance of the GSI/GFS system when assimilating soundings of GPS RO we finally conducted a cycling assimilation experiment with three different runs: CTL, the control using the same observations as used in operations; REF, where profiles of $N$ were additionally assimilated; and BND, where soundings of $\alpha$ (instead of $N$) were assimilated on top of the current observations. We should mention here that in all the verifications plots discussed in this section, each experiment is verified against its own analysis.

We ran the GSI/GFS system from 1 July to 31 August 2005, with an assimilation time window of 6 h. In REF (BND) experiment, around 40–50 profiles of $N$ ($\alpha$) were assimilated per analysis cycle on top of all observations currently used in operations. Because of computer resources, we used the lower T62 horizontal resolution model (~200 km in a Gaussian grid), but we kept the same high vertical resolution (64 levels) as in the previous experiments. These preliminary tests at lower resolution are consistent with the regular practice at NCEP to evaluate the potential impact of new observations. As the control experiment (CTL) was also run at lower resolution we would expect most of the results found at T62 still to be valid at a higher horizontal resolution. The results of these experiments enable us to directly compare the impact of soundings of refractivity and bending angle. Also, GPS RO data are characterized by high vertical resolution but lower horizontal resolution (~300 km), which further justifies the use of a lower-resolution model for these preliminary impact studies.

Figures 8, 9, and 10 show the anomaly correlation (AC) as a function of the forecast length for the 200-hPa temperature in the Northern Hemisphere, Tropics, and Southern Hemisphere, respectively. From Figs. 9 and 10, the assimilation of GPS RO is improving AC scores in both REF and BND. In the Tropics (Fig. 9) the differences between REF and CTL are statistically significant at the 25% level for day 3, when calculated with the Student’s $t$ test. The differences are statistically more significant between BND and CTL (at the level of 10% for day 4). Differences with the CTL are statistically less significant in the Southern Hemisphere (at ~28% level for REF and ~40% for BND for day 4 with the Student’s $t$ test).

The AC at day 4 increases by 0.014 in REF and 0.01
in BND in the Southern Hemisphere (Fig. 10) and by 0.02 in REF and 0.03 in BND in the Tropics (Fig. 9). Overall, the increase in AC starts at a 48-h forecast in the Southern Hemisphere and a bit earlier in the Tropics (at a 24-h forecast). There is not a clear pattern that indicates which strategy seems to be more appropriate. While in the Tropics BND seems to perform slightly better at forecast days 3 and 4 (Fig. 9), the opposite situation is found in the Southern Hemisphere (Fig. 10). In the Southern Hemisphere, the differences between REF and BND are statistically significant at the 0.001% and 0.07% level for days 1 and 2, respectively, when calculated with the Student’s t test. In general, REF is doing a better job than BND in the Southern Hemisphere, while in the Tropics results seem to vary with the forecast range. However, tropical differences between REF and BND are only statistically different at the 50% level for day 4.

On average, in the Southern Hemisphere (Tropics) the AC score increases by 0.01 (0.02) in REF and 0.005 (0.02) in BND. When looking at the scores in the Northern Hemisphere (Fig. 8), the assimilation of GPS RO is slightly degrading the AC skills (0.006 in REF and 0.015 in BND, on average). The differences between REF and BND are statistically significant at the 5% and 10% levels for days 2 and 3, respectively. Experiments REF (BND) and CTL are different at the 22% (0.1%) and 25% (1%) levels for days 2 and 3, respectively.

As the AC score is insensitive to biases, we show in Figs. 11, 12, and 13 the root-mean-squared (rms; Figs. 11a, 12a, and 13a) and the mean (Figs. 11b, 12b, and 13b) differences between the forecasts and their own analyses at the same level and for the same variable. It is evident from the figures that GPS RO reduces the bias globally. In fact, the results seem to indicate that the model is creating some bias and the GPS RO helps to correct them. Understanding the causes of possible biases in the NCEP model is under current research. New types of observations capable of correcting for this bias would be extremely helpful at NCEP in order to improve the GFS climatology. BND seems to perform a better job in the Northern (Fig. 11) and Southern (Fig. 13) Hemispheres. However, REF is slightly superior in the Tropics (Fig. 12). In the Tropics, the assimilation of $\alpha$ is actually changing the sign of the bias. Comparing with observations, the bias is decreasing in the right direction, as the observations of GPS are producing warmer analyses and forecasts than the CTL.

Looking at the rms scores, the errors are reduced in Northern and Southern Hemispheres (by 0.35 K at day 5) and the impact is found to be neutral in the Tropics. Similar results are found at 300 and 100 hPa, as well as at lower altitudes. In general, GPS RO globally reduces biases and rms errors while some improvements in AC scores are found in the Southern Hemisphere and Tropics. A slight AC degradation is found at 200 and 300 hPa in the Northern Hemisphere. This seems
to suggest that a more restrictive QC needs to be applied in the summer Hemisphere in order to not degrade AC scores. The fact that the AC score degrades but the bias is removed might be caused by some noisy (low scale) structures present in the analysis due to the assimilation of bad profiles that pass our QC checks. These unrealistic structures would in turn be propagated in time with the forecast model, resulting in a degradation of the AC score. Another possibility is that the structures might be correct, but the model forecast is introducing or modifying them in an unrealistic or dynamically unbalanced way. At the same time, the mean difference between forecasts and analyses might decrease as a consequence of the introduction of the lower-scale structures.

As we have assimilated GPS RO at low altitudes, we also find some impact on the humidity field. Biases and rms errors at 925 hPa for the specific humidity are shown in Fig. 14 (Northern Hemisphere), Fig. 15 (Tropics), and Fig. 16 (Southern Hemisphere). Even though there is neutral impact on the rms error, GPS RO is globally correcting for biases. Similar results are found at other altitudes: neutral with respect to the rms errors but with a marked tendency to reduce the bias. In general, AC scores show neutral or slightly positive impact from the assimilation of GPS observations (not shown). These are encouraging results that suggest that GPS RO might improve the analyses and forecasts of precipitation. Indeed, some preliminary investigation of the precipitation field in REF and BND indicates that the assimilation of GPS RO observations slightly improves the forecast scores of precipitation over North America.

The AC scores for 500Z in the Southern Hemisphere show a slightly positive impact (0.018) starting at day 5 when soundings of N are assimilated into the system (Fig. 17). The impact is found to be neutral in BND. Differences between REF and CTL are statistically significant at the $\sim$50% level for day 6 with the Student’s $t$ test. As found for the temperature field, the biases at 500Z in the Southern Hemisphere are also reduced in BND and REF (Fig. 18). These results differ considerably from those presented in Healy and Thépaut (2006) as we did not remove the increments of surface pressure in BND. Those authors found a clear degradation of the 500Z AC scores as a result of increments of surface pressure introduced by the assimilation of GPS RO observations. In our experiments, the comparison of the surface pressure field in CTL, REF, and BND against the observations showed a statistically neutral impact of the assimilation of GPS on surface pressure. In the Northern Hemisphere, the biases are also reduced when soundings of GPS RO are assimilated while the AC scores show neutral impact (not shown).

The AC score for the north–south wind component of the 200-hPa tropical winds shows a slightly positive impact...
tendency starting at day 5 in both REF and BND experiments (not shown). The improvement of this variable would surely result in an improvement in the analysis and forecast of the tropical cyclonic activity.

6. Conclusions

In preparation for the operational assimilation of the COSMIC data and other future GPS RO missions, the NOAA/NWS has developed the infrastructure necessary to assimilate quasi-vertical profiles of refractivity and bending angle. Both types of observations are products derived from the raw GPS RO measurements by UCAR.

We have successfully developed, tested, and implemented an appropriate forward model to transform the analysis variables into the form of the $N$ or $\alpha$, the tangent linear and adjoint codes of the forward model, and preliminary error structures and quality control procedures. A difference from previous work is that our bending angle forward operator is computationally faster and involves fewer numerical approximations in order to solve the integral.

The assimilation of both types of GPS RO observations is proven to behave well and different increment structures are found depending on the type of forward operator being used. This is partially caused by the different type of observation being assimilated ($\alpha$ versus $N$). However, the fact that each forward model is implemented with its own QC and error characterization largely affects the results of the experiments. In addition, when the GPS RO observations are assimilated along with other currently available data the indirect impact of the GPS RO on the QC of other observations might also modify the analysis increments.

We must emphasize that our motivation as a NWP center is to compare two different assimilation strategies and not two different types of observations. Indeed, this is the only way we can evaluate the benefits of a new observing system in an operational framework. In this regard, we believe this is the first time that a fair comparison between observations of $N$ and $\alpha$ is being evaluated in an operational center. Due to the limitation of computer resources, the forecast trials analyzed in this study were not conducted at full resolution.

We have also shown some encouraging preliminary results that suggest the benefits we can obtain from assimilating GPS RO observations in weather analysis and forecasting. Results indicate a positive impact on fields not just directly related to the GPS forward model such as temperature and humidity, but on other fields, like winds, owing to the propagation of information via the background error correlations.

Results show improvement of temperature forecast anomaly correlation scores at 200 hPa in the Southern Hemisphere by 0.01 when observations of $N$ are assimilated on top of the other current data. In the Tropics, a larger improvement (~0.02) is found when GPS RO observations are included in the system. At lower altitudes, a neutral or slightly positive impact is found for all latitudes. However, the use of GPS RO results in a slight degradation in the Northern Hemisphere in the upper troposphere and stratosphere. This might be re-

![Fig. 16. Same as in Fig. 15, but in the Southern Hemisphere.](image1)

![Fig. 17. Anomaly correlation scores for the 500-hPa geopotential heights in the Southern Hemisphere for CTL, REF, and BND, 0000 UTC 10 Jul–31 Aug 2005.](image2)
lated to an inappropriate QC of the GPS RO data in the summer hemisphere or/and the use of a lower model resolution in these early experiments. Globally, biases are largely corrected for and rms errors are slightly reduced after assimilating GPS RO observations.

In contrast to other earlier studies, we have also assimilated observations in the lower troposphere, allowing increments to the humidity field. In general, results found at the lower model levels are also very encouraging. Even if the impact on the rms scores seems to be rather neutral, there is a clear tendency of the GPS RO data to reduce the biases, this benefit being more significant when soundings of $\alpha$ are assimilated.

Unlike the results found at ECMWF, the implementation of our forward operator for $\alpha$ does not require switching off the surface pressure increments in order to not degrade the scores of 500Z in the Southern Hemisphere. Our experiments show an improvement of 500Z forecasts starting at day 5 of around 0.01 in the anomaly correlation score. Bias reduction and slightly improved anomaly correlation scores are also found for 200-hPa tropical winds, which suggests the potential of the GPS RO data to improve forecasting the development and steering of tropical activity.

Even if an overall slight positive impact in forecast skills is found with the use of GPS RO observations, it is not clear yet which of either forward models ($N$ or $\alpha$) is performing a better job. We have found that, in some cases, the assimilation of bending angles seems superior to the assimilation of refractivities, but the opposite situation is also found.

It is important to emphasize that the results presented in this work are preliminary results of the impact of GPS RO observations at NCEP/EMC. The tuning of the system in both $N$ and $\alpha$ cases is still under current research and more investigation needs to be conducted before the response of the model to the GPS RO is fully understood and, consequently, a forward operator can be selected and the data can be routinely assimilated in operations. The results of this ongoing research will be discussed in detail in a follow-up publication.

The assumption of local spherical symmetry, including the neglected horizontal refractivity gradients, is a significant shortcoming of the two forward operators described in this paper. It is important to point out that, not only do atmospheric variables change horizontally along the direction of the rays, but, also owing to the fact that the rays themselves sweep out an oblique transverse horizontal component of gradients. Indeed, the real geometry of a radio occultation is not as simple as Fig. 1 seems to imply, but involves an inclination away from vertical of the surface swept out by the occulting rays (a surface moreover, that is not in general even a plane). We plan to attempt improvements on the deficiencies of the local forward operators presented in this paper in future extensions of this ongoing work. It is also evident that the upcoming COSMIC data stream will also require further tuning of the system since only CHAMP data in a nonoperational mode have been available for testing and tuning of our assimilation strategies.

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