Preliminary Impact Studies Using Global Positioning System Radio Occultation Profiles at NCEP

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Abstract

Following the successful launch of the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) satellites in April 2006, NCEP's Environmental Modeling Center (EMC) is planning to use the COSMIC data in its next-generation Global Data Assimilation System. In preparation for the assimilation of GPS radio occultation (RO) data from COSMIC and other missions, NCEP/EMC has developed the infrastructure necessary to use profiles of refractivity and bending angle in an operational framework. In both forward operators, horizontal gradients of refractivity have been neglected and each operator has been tuned with its corresponding quality control checks and error characterization. In this paper, the benefits of the assimilation of profiles of GPS RO on top of the current observations being regularly used in operations are analyzed. In addition, differences between the assimilation of bending angle and refractivity are discussed. To avoid unrealistic increments within the higher model layers, experiments not using GPS RO observations above 30 km are also performed. This stratospheric data assimilation problem was present in earlier experiments with GPS RO data at NCEP/EMC and impacted the forecast in the lower-atmospheric levels as well as the stratosphere. Some characteristics of the assimilation of profiles of bending angle are also discussed. Data from the Challenging Minisatellite Payload (CHAMP) satellite are available in non–real time at NOAA and have been used to perform the experiments examined herein.

1. Introduction

The Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) project (Anthes et al. 2000) successfully launched six small satellites on 15 April 2006, each carrying a GPS radio occultation (RO) receiver. We refer to earlier studies (Hajj et al. 1994, 2002; Kursinski et al. 1996; Rocken et al. 1997; Kuo et al. 2004) for descriptions of the methodology of the GPS RO technology and only a summary of the atmospheric products basics is presented here.

Each of the low-earth-orbit (LEO) GPS RO receivers takes measurements of the phase and amplitude of the two GPS signals and, together with the knowledge of the positions and velocities of the GPS and COSMIC satellites, profiles of bending angle as a function of the asymptotic miss distance are constructed for each signal under the assumption of spherical symmetry. Because of the dispersive nature of the ionosphere at the GPS frequencies, the contribution of the ionosphere can be largely removed by constructing an appropriate linear combination of the bending angle for each signal. With the use of climatology and the assumption of local spherical symmetry, profiles of ionospheric-compensated...
sated bending angle can be inverted through an Abel transform, obtaining profiles of refractivity as a function of the geometric height.

The impact of the assimilation of profiles of bending angle and refractivity in data assimilation systems has been analyzed in several studies (Liu et al. 2001; Poli and Joiner 2003; Zou et al. 2004; Wee and Kuo 2004; Cucurull et al. 2006). However, these authors either did not make use of all of the observations available in operations, or used older versions of meteorological models. In operational numerical weather prediction (NWP) centers, the Met Office has developed the capability to assimilate soundings of refractivity (Healy et al. 2005), and profiles of bending angle can be assimilated at the European Centre for Medium-Range Weather Forecasts (ECMWF; Healy and Thépaut 2006). At the time this paper was written, only the Met Office, ECMWF, and Japanese Meteorological Agency (JMA) assimilated GPS RO data from the Challenging Minisatellite Payload (CHAMP) satellite mission (Wickert et al. 2001) in an operational framework. Observations from the CHAMP satellite are not being operationally assimilated at the National Oceanic and Atmospheric Administration (NOAA) because, at the time this work was done, CHAMP data were not available in real time at NOAA.

In preparation for the assimilation of COSMIC products and those of other future GPS RO missions into the National Centers for Environmental Prediction’s (NCEP’s) Global Data Assimilation System, the U.S. NOAA/National Weather Service (NWS) has developed the capability to assimilate profiles of bending angle and refractivity. A detailed description of the forward operators and quality control procedures implemented at NOAA/NWS for the assimilation of GPS RO observations is provided in Cucurull et al. (2007, hereinafter C07). This study also evaluates some preliminary results on the assimilation of observations of bending angle versus refractivity. As far as we know, this has been the first attempt to assess the comparative performance of the two types of GPS RO observations by using the same data assimilation system in an operational NWP center.

In this paper, we analyze with further detail the strengths and weaknesses of NCEP’s system and the use of profiles of bending angle and refractivity. This work is a follow-up on the early results presented in C07, where the main focus of the study was to demonstrate that NCEP’s Environmental Modeling Center (EMC) had developed the implementation of the forward operators, quality control procedures, and errors characterization necessary to assimilate soundings of bending angle and refractivity. Our focus here is to use the infrastructure described in C07 to conduct some preliminary impact experiments in order to evaluate the benefits of the GPS RO in weather analysis and forecasts.

We should point out that at the time this paper was written, NOAA was getting COSMIC data on a continuous basis, but we have not yet had a significant amount of data over a long enough period to get statistically significant results. Instead, observations from the earlier CHAMP mission were used in the experiments. The fact that both the COSMIC and CHAMP payloads share similar receiver technology provides an excellent opportunity to analyze the potential impact of the GPS RO observations provided by COSMIC.

The paper is structured as follows: section 2 briefly reviews the forward operators and quality control procedures used in the experiments that are described with more detail in C07. The experiment setup is presented in section 3, and the results for the different experiments are analyzed in section 4. A summary is given in section 5.

2. Review of observation operators

a. Refractivity data

The forward operator used to simulate observations of refractivity as a function of the geometric height \( z \) is composed of the following steps:

1) Compute model geopotential heights at the location of the observation.
2) Convert \( z \) to geopotential height to locate the observation within the model’s vertical grid.
3) Interpolate model profiles of pressure, temperature, and water vapor pressure to the location of the observation.
4) Get model refractivity \( N \) by evaluating (Smith and Weintraub 1953)

\[
N = 77.6 \left( \frac{P}{T} \right) + 3.73 \times 10^5 \left( \frac{P_v}{T^2} \right),
\]

where \( P \) is the total atmospheric pressure (hPa), \( T \) is the atmospheric temperature (K), and \( P_v \) is the partial pressure of water vapor (hPa). The quality control implemented in the code is based on a month-long comparison between observations and forecasts of \( N \). In the assimilation system, observations are rejected either if they deviate more than three standard deviations from the forecast (C07) or if an observation above it in the same profile is rejected (due to residual ionospheric errors and mostly tracking errors in the lower troposphere). The statistics
used to accept or reject an observation are computed once, and they are not reevaluated during the cycling experiments.

b. Bending-angle data

Forecasts of bending angle ($\alpha$) as a function of the asymptote miss distance (or “impact parameter”) $a$ are computed by evaluating the following integral:

$$\alpha(a) = -2a \int_a^\infty \frac{d \ln n}{dx} dx \ (x = nr),$$

(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. The impact parameter remains constant along the trajectory of a ray for a spherically symmetric atmosphere. The singularity in the integrand at $x = a$ can be overcome by evaluating the integral on a new grid $s$, where

$$x = \sqrt{a^2 + s^2}.$$

(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. The motivation for using an equally spaced grid is to ensure small truncation error when evaluating the integral. The new grid has a spacing of 5 km, with 161 levels in the vertical. In summary, the procedure used to convert model variables to bending angles is as follows:

1) Model profiles of geopotential heights and $N$ are computed at the location of the observation. Geopotential heights are then converted to $z$.
2) The radius $r$ is obtained by adding $z$ to the radius of curvature of the local spherical fit to the ellipsoid. (This value is provided in the observation files.)
3) Profiles of $N$ are converted to refractive index profiles, $n = 1 + 10^{-8}N$.
4) Model profiles of refractive radius $x = nr$ are calculated.
5) Both $n$ and $x$ are extrapolated above the model top by assuming an exponential decay for $N$ within the two uppermost layers. The model top is located at 0.266 hPa ($\sim 60$ km) and the spacing between the midpoints of the two uppermost layers is $\sim 6$ km. In the new grid $s$, the profile is extrapolated to a height of $\sim 800$ km.
6) Model profiles of $n$ and $x$ are interpolated to the new grid $s$.
7) The integrand in (2) is computed on the new grid $s$.
8) The integral is evaluated in an equally spaced grid.

As in the case of refractivity, an observation is rejected if either it deviates more than three standard deviations from its forecast counterpart or, if it is below 10 km, any observation above it in the same profile is rejected. The statistics are based on the same-month comparison between observations and forecasts of $\alpha$ as used in the case of refractivity. Once again, the statistics are only computed once and they are not updated during the experiments.

3. Experiment setup

The experiments conducted in this study use an early version of the gridpoint statistical interpolation (GSI) analysis code (Wu et al. 2002) coupled with the NCEP/Global Forecast System (GFS). (The GSI was operationally implemented at NCEP in May 2007.) All of the observations being used in operations, including the Atmospheric Infrared Sounder (AIRS) radiances, are assimilated in the control (CTL) experiment. In the first set of two additional experiments, we include GPS RO data in addition to the current observations; observations of refractivity are assimilated in experiment REF while bending angles are included in experiment BND. It is important to emphasize that the observations of refractivity and bending angle are subject to different quality control procedures and present different error characteristics (C07), so the differences obtained between REF and BND are not only limited to the type of observation being assimilated. The amount of observations being rejected with the quality control described in section 2 is $\sim 4\%$.

We ran experiments CTL, REF, and BND from 1 July to 31 August 2005, with an assimilation time window of 6 h. The number of GPS RO profiles available for assimilation per analysis cycle ranged between 40 and 50. The system ran with a horizontal resolution of T62 ($\sim 200$ km in a Gaussian grid) and 64 levels in the vertical (from surface to $\sim 0.26$ hPa). The use of a lower horizontal resolution as compared to operations (T382, $\sim 35$ km) is due to the limited computer resources at NCEP and is justified by the fact that observations of GPS RO are characterized by lower horizontal resolution ($\sim 300$ km). The vertical resolution used in all of the experiments is the same as in the operations (64 levels). This is a standard procedure followed at NCEP/EMC in order to conduct preliminary impact studies of a new type of dataset. Some of the quantitative conclusions derived from these experiments might not still be valid when using a higher-resolution model. However, we expect the qualitative response of the model to the characteristics of this new instrument to be similar.

In a second set of assimilation experiments, REFP and BNDP, we reject GPS RO observations of refractivity and bending angle, respectively, above 30 km
(these observations are usually provided from a few meters above the surface to ~40 km). The motivation for not using high-level observations arises from the fact that REF and BND were found to produce unrealistic analysis increments at the higher model levels (see section 4c). From our study, this problem seems to be related to the specification of our background error covariance matrix. A summary of the different sets of experiments is presented in Table 1.

4. Results

a. Assimilation of profiles of bending angle versus refractivity

This section analyzes the results obtained in experiments REF and BND (see Table 1), where all the observations are assimilated, provided they pass the quality control checks described in section 2. Results from both experiments are evaluated against the control, CTL. For each experiment, forecasts are verified against their own analyses. Some of the results presented in this section for REF and BND were introduced in C07. We do review their more significant findings here in order to evaluate the benefits obtained from experiments REFP and BNDP, described in detail in section 4c.

Figure 1 shows the 500-hPa geopotential height 5-day forecast anomaly correlation (AC) in CTL, REF, and BND for the northern (NH; 20°–80°N) and southern (SH; 20°–80°S) extratropics. The assimilation of the profiles of bending angle slightly degrades the AC score in both extratropics, with a larger degradation (of 1.1%) found in the northern extratropics. Benefits from the assimilation of GPS RO are only observed for REF in the southern extratropics (Fig. 1). When profiles of $\alpha$ are assimilated instead of $N$, the AC score for the 200-hPa temperature also improves as compared to CTL (the BND curve is between CTL and REF in Fig. 6). Differences between REF (BND) and CTL are statistically significant at 28% (40%) for day 4 with the Student’s $t$ test.

A summary of the anomaly correlation scores at 1–7 days for the different experiments is shown in Figs. 4, 5, and 6 for the northern extratropics, tropics, and southern extratropics, respectively. Summarizing what is discussed in C07, the assimilation of profiles of $N$ in REF increases AC scores for the 200-hPa temperature in the southern extratropics (Fig. 6). When profiles of $\alpha$ are assimilated instead of $N$, the AC score for the 200-hPa temperature also improves as compared to CTL (the BND curve is between CTL and REF in Fig. 6). Differences between REF (BND) and CTL are statistically significant at 28% (40%) for day 4 with the Student’s $t$ test.
test. However, a slight degradation is apparent in the northern extratropics (Fig. 4), when observations of α are assimilated in BND at 200 hPa (there is a decrease of 0.02 at day 5). In the northern extratropics, the AC score for temperature at 200 hPa slightly improves in REF as compared to BND, but forecasts are still slightly less accurate than in CTL (Fig. 4). The assimilation of RO profiles performs better in the tropical latitudes (Fig. 5) where AC scores for temperature improve at 200 hPa (0.022 in REF and 0.019 in BND at day 5). The differences in the tropics between REF and CTL are statistically significant at the 25% level for day 3, as calculated with the Student’s t test. Trials BND and CTL show a more statistically significant difference (at the 18% level for day 3).

C07 showed that the assimilation of GPS RO (refractivities and bending angles) results in a clear reduction of the model temperature bias for all latitudes. The rms error and mean difference for the 200-hPa temperature for experiments REF, BND, and CTL are plotted in Figs. 7, 8, and 9 for the northern extratropics, tropics, and southern extratropics, respectively. From the figures, the bias reduction as a function of the forecast day in BND as compared to the CTL is very significant. A reduction of the rms error in REF and BND at ex-

![Fig. 3. Root-mean-square difference at day 2 for the tropical (20°S–20°N) north–south wind component (m s⁻¹) at 200 hPa for the different experiments: CTL (plus signs), REF (open circles), BND (filled circles), REFP (open squares), and BNDP (filled squares).](image)

![Fig. 4. Anomaly correlation scores for the temperature field at 200 hPa in the northern extratropics (20°–80°N) as a function of the forecast length. The graphs for REFP and CTL are closely clustered. The results are filtered to represent the structures with total wavenumber 1–20.](image)

![Fig. 5. Anomaly correlation scores for the temperature field at 200 hPa in the tropics as a function of the forecast length. The graphs for BNDP and BND are closely clustered. The results are filtered to represent the structures with total wavenumber 1–20.](image)
tended forecast ranges is also evident in the northern
and southern extratropics.

Owing to the fact that low-level observations are
used in the assimilation system, provided they pass the
quality control checks, an impact of the use of GPS RO
observations at lower elevations is also found. The im-
pact is found to be more significant in the southern
extratropics (not shown), probably because there are
less conventional observations there than at other lati-
tudes.

The fact that the assimilation of GPS RO observa-
tions results in a clear reduction of the model bias for
all latitudes, while the AC scores do not necessarily
improve, should not come as a surprise. The AC score
does not contain information on biases; it is just a mea-
sure of the consistency of the model’s forecast anomaly
against its own analyzed anomaly.

b. Considerations on the assimilation of profiles of
bending angle

One of the challenges of the assimilation of observa-
tions of bending angle is how the model resolves the
vertical structure characteristics of the profiles of bend-
ing angle. Profiles of bending angle show rapid varia-
tions with height resulting from vertical refractivity gra-
dients, which produce larger differences between the
observations and model simulations. The rapid variabil-
ity of these differences is largely smoothed out by the
use of an Abel inversion in the retrieval of refractivities
from soundings of bending angle. This makes the as-
similation of bending angles more difficult than the as-
similation of the profiles of refractivity. To understand
this aspect of the assimilation of bending angles, Fig. 10
shows the fractional difference between the observa-
tions of bending angle and model simulations from
(left) the background and (right) the analysis as a func-
tion of the impact height (impact parameter minus the
local radius of curvature of the earth) for three differ-
ent profiles. In the figure, the three tropical profiles
occurred on 6 August 2005 and are plotted as continu-
ous, dashed, and dotted lines. As shown in Fig. 10 (left),
all three profiles show higher horizontal variance at
lower altitudes (<10 km). The variability is also signif-
ificant for altitudes >30 km. After the minimization al-
gorithm, the horizontal variance of the differences be-
tween the observations, and the analysis is largely re-
duced (right). This indicates that the minimization
algorithm does a good job fitting the observations. A
smaller reduction of the fractional difference is ob-

Fig. 6. Anomaly correlation scores for the temperature field at
200 hPa in the southern extratropics (20°–80°S) as a function of
the forecast length. The graph BND is closely clustered to those of
REFP and BNDP. The results are filtered to represent the struc-
tures with total wavenumber 1–20.

Fig. 7. (a) Root-mean-square difference and (b) mean difference (K) for the temperature at 200 hPa in the
northern extratropics (20°–80°N). The graphs for REFP and CTL are closely clustered in (a) and (b), as are those
for REF, BND, and BNDP in (a).
served in the lower troposphere for all three profiles. After the minimization, the values still reach around 10% difference in bending angle. This might be caused by less accurate low-level observations being assimilated, by real atmospheric structures being unresolved by the model because of its lower horizontal resolution, by errors in the forward operator resulting from horizontal gradients in refractivity (being neglected in the forward operator), or any combination thereof.

Figure 11 shows the absolute observed and simulated bending angles corresponding to the same profiles presented in Fig. 10 in fractional differences. Observed values are indicated in the top panel, while simulations from the background and analysis fields are shown in the center and bottom panels, respectively. It is noticeable from Fig. 11 (top), that all three profiles show large and rapid changes in bending angle in the lower troposphere. However, the background field (center) only detects these rapid changes in two of them (profiles shown as continuous and dotted lines). The structures show a much coarser resolution than that in the observed profiles because of the lower resolution of the model. Once the profiles are assimilated in Fig. 11 (bottom), the analysis reproduces the steplike structures of the continuous and dotted profiles quite well. However, it does not alter the structure of the smoother profile (profile shown as a dashed line). This behavior was found in many other cases and suggests that in order for the model to capture significant changes in bending angle, the structures need to be already present in the background field. In other words, the analysis adjusts structures that already exist in the background field in order to fit the observations, but it cannot create strong vertical gradients in refractivity when they are not present in the background field.

The structures in the observed profiles of bending

![Fig. 8](image8.png)

**Fig. 8.** (a) Root-mean-square difference and (b) mean difference (K) for the temperature at 200 hPa in the tropics.

![Fig. 9](image9.png)

**Fig. 9.** (a) Root-mean-square difference and (b) mean difference (K) for the temperature at 200 hPa in the southern extratropics (20°–80°S). In (a), the graphs for REFP and CTL are closely clustered, as are those for REF, BND, and BNDP.
angle along the depth of the atmosphere might well be real (e.g., gravity waves in the stratosphere). However, the model might not have a sufficient resolution to resolve them. Consequently, the high-frequency structures in the innovation increments should be filtered in the assimilation system according to the resolution of the model. In addition, the use of “superobbing” to account for the different vertical resolution between GPS RO profiles and the model (C07) should further enable the removal of the higher vertical frequencies. In other situations, though, the retrieved bending angles might be less accurate at lower levels. In the lower troposphere, strong refractivity gradients, mainly caused by complicated structures of the water vapor, result in the multipath propagation between the transmitter and receiver. The multiple rays arriving concurrently at the receiver are resolved in RO signal processing by applying radio holographic methods (Sokolovskiy 2001; Gorbunov 2002; Jensen et al. 2003). These methods transform the RO signal from time coordinate to impact parameter representation. In that representation, the bending angle is a single-valued (however, nonmonotone) function, and it can be assimilated regardless of the existence of the multipath propagation in real observations. Thus, with the application of radio holographic methods, the multipath propagation induced by spherically symmetric refractivity structures does not introduce errors in bending angles. However, nonspherically symmetric refractivity structures, such as those induced by turbulence and convection of moist air, do introduce errors in the bending angles, which may be especially significant in the moist lower troposphere (S. Sokolovskiy 2007, personal communication).

c. Stratospheric data assimilation

Results shown in Figs. 7, 8, and 9 clearly indicate a reduction of the model bias in experiments REF and BND as compared to CTL. However, in each experiment forecasts were validated against their own analyses. To verify whether the reduction of the bias in BND and REF is real or just apparent, we should also verify the experiments against observations. Analysis and forecast fits to radiosondes (not shown) revealed a significant increase of the bias in BND and a slight increase in REF experiments at higher altitudes. These large and unrealistic biases as compared to CTL extended to other latitudes and higher altitudes. To understand the differences between the CTL and the GPS RO experiments, we depict in Fig. 12 the 1-hPa temperature difference between CTL and the GPS RO experiments. The difference between CTL and REF is plotted in Fig. 12a, and the difference between CTL and BND in Fig. 12b. Both plots correspond to the 2-month-averaged campaign. The unrealistic differences between the CTL and the runs with GPS RO extend to higher altitudes (above ~1 hPa) and do not exist at lower levels. The stratospheric data assimilation problem seems to be confined to higher altitudes in experiments REF and BND. However, note that the effects might have propagated downward while cycling, thus altering the results within the lower model layers. (It is apparent from the figure that the use of GPS RO data is producing much cooler analyses, as compared to the CTL. This is consistent with the results found when validating against observations.) The structures resulting from the assimilation of bending angle in BND (Fig. 12b) are more severe (up to 45 K cooler than CTL), and
extend to a larger area, than when observations of refractivity are used (Fig. 12a). It is important to remark that we conducted several tests by modifying the quality control checks and error characterization without obtaining any significant improvement at the higher model layers. In another experiment, we increased the horizontal resolution of the model to the one used in operations, but the unrealistic structures in the stratosphere remained. It is apparent from Fig. 12 that there is a strong latitude dependency of the results. It is not clear why the effects should be worse in the southern extratropics. The fact that models are less accurate in the winter (southern) pole at the higher layers and that errors propagate in a lower number of assimilation

Fig. 11. Profiles of (top) observed and simulated bending angles from the (center) background and (bottom) analysis fields as a function of the impact height. The plots are shown for the three tropical profiles shown in Fig. 10.
cycles in the southern latitudes might be the reason for the larger unrealistic structures in the southern extratropics.

A deeper analysis of the impact of GPS RO in REF and BND clearly showed that the increments obtained at the higher levels were relatively small at the beginning of the campaign, but they increased in the course of cycling the assimilation scheme. This process was quite rapid and large increments (~20 K) were already evident after a few cycles of assimilating GPS RO observations. This was found to be the result of combining relatively accurate high-level observations with a larger variance in the background error covariance matrix at these high model layers. After a few cycles, the obser-
vation increments of the higher-level observations were easily projected to the highest model layers. This resulted in unrealistic analysis increments after the continuous assimilation of GPS RO data. This behavior is inherent to the NCEP analysis and not to the GPS RO observations. Future work at NCEP will address this problem in order to fully exploit the amount of GPS RO observations available for assimilation.

To compensate for these effects, observations of refractivity and bending angle above 30 km were rejected from the assimilation system in REFP and BNDP, respectively (see Table 1). The benefits of such an adjustment can be seen in Fig. 13, where the zonal mean temperature at 1 hPa at 0000 UTC 12 July 2005 has been plotted for the different experiments. Before the rejection of the high-level observations in REF (open square) and BND (open circle), it is clear that a cold bias is present in the lower latitudes in REF and globally in BND as compared to CTL (filled circle). The differences between BND and REF are more significant in the southern extratropics. Experiment BND is cooling the lower latitudes more than 35 K, when compared to the CTL. The curve corresponding to REFP cannot be distinguished in the figure from that of the CTL, indicating that the large differences between REF and CTL have been removed when the high-level observations are rejected from the data assimilation system in REFP. In the case of the assimilation of observations of bending angle, the differences from the CTL experiment are largely reduced in BNDP (plus).

The nonuse of high-level observations in REFP slightly improves the 500-hPa day-5 geopotential heights in both extratropics, while BNDP is found to be neutral in the southern extratropics and a slight degradation can be noticed in the northern extratropics (Fig. 1). From the comparison along the extended forecast range, REFP and BNDP show a neutral impact in the southern extratropics when compared to REF and BND, respectively (Fig. 2). A slight degradation is found for the day-2 tropical winds at 200 hPa, where REF and BND perform slightly better than REFP and BNDP, respectively (Fig. 3). However, the results are neutral when compared to CTL.

AC scores for temperature for experiments REFP and BNDP as a function of the forecast day for the whole campaign are shown in Figs. 4, 5, and 6 for the northern extratropics, tropics, and southern extratropics, respectively. The figures show the AC scores for the temperature variable at 200 hPa and can be compared with trials of CTL, REF, and BND. It is remarkable from Fig. 4 that the slight degradation found in REF in the northern extratropics is totally removed in REFP.

![Fig. 13. Zonal mean temperature at 1 hPa as a function of latitude valid at 0000 UTC 12 Jul 2005 for the different experiments: CTL (filled circle), REF (open square), BND (open circle), REFP (filled square; on top of CTL), and BNDP (plus sign).](image-url)
(differences between REF and REFP are statistically significant at the 23% level for day 3 with the Student’s \( t \) test). Experiments REFP and CTL show similar scores as a function of the forecast day. The assimilation of bending angles is still showing a slight degradation in the northern extratropics; however BNDP is performing better than BND for all forecast ranges (statistically significant at 26% level for day 3). The differences between BNDP and CTL in the northern extratropics are statistically significant at the 14% level for day 3.

In the tropics and southern extratropics, REFP and BNDP still show better AC scores than CTL. In the tropics (Fig. 5), REFP is performing slightly worse than REF (differences are significant at the 33% level for day 3 with the Student’s \( t \) test), but still better than CTL. Experiments BND and BNDP show similar performances in the tropics (Fig. 5) and southern latitudes (Fig. 6). (In Figs. 5 and 6, BND cannot be distinguished from BNDP.) In the southern extratropics (Fig. 6), the nonuse of high-level observations in REFP and BNDP produces similar AC scores as in experiment BND. This suggests that, in general, the larger effects of rejecting observations within the higher layers are found with the assimilation of observations of refractivity. The differences between REF and REFP in the southern extratropics start being significant at day 5. This is also valid in the tropical latitudes, where differences between REF and REFP are noticeable starting at day 2.

The larger impact of rejecting high-level observations in the case of refractivity as compared to the assimilation of bending angle can be extended to the rms and bias scores. In the northern extratropics, Fig. 7 shows a significant reduction of the model bias in experiment BNDP (but less reduction than in BND), while REFP shows a neutral impact when compared to CTL and a larger bias than REF (Fig. 7b). The significant reduction of the rms error, found in experiments REF, BND, and BNDP is mostly lost in REFP (Fig. 7a). In the tropics (Fig. 8), no impact is found in the rms error (all of the experiments with GPS RO show neutral impacts as compared to CTL) and a slight loss in skill in reducing the bias is found in BNPD as compared with BND. Once again, experiments REF and REFP show larger differences than experiments BND and BNDP. Similar results are found in the lower latitudes (Fig. 9). In this case though, and differently from Fig. 8b, all experiments are negatively biased, with the CTL being the most biased of all. BNDP is reducing the bias created by the model most effectively. Experiment REFP reduces the rms error less than REF.

5. Conclusions

Following the methodology described in C07, and in preparation for the assimilation of GPS RO COSMIC data operationally, we have highlighted the benefits and potential problems of using GPS RO data in the next-generation NCEP Global Data Assimilation System.

The results we presented in an earlier study with the GSI/GFS system showed that the GPS RO data were improving anomaly correlation scores for the 200-hPa temperature field in the southern extratropics and tropical latitudes, while a slight degradation was found in the northern extratropics. This result was found with the use of the two local observation operators that were being tested for assimilation of GPS RO observations, bending angle, and refractivity. A significant overall reduction of the model bias and root-mean-square error was achieved when profiles of GPS RO were assimilated in the system.

In this paper we have now shown that those early experiments suffered from the effects of unrealistic structures present in the upper model levels. Even if this stratospheric problem is confined to the uppermost levels, the large increments in temperature might have propagated downward while cycling, thus damaging the lower-atmospheric levels. These spurious structures have been shown to be the result of a combination of larger variances associated with the top levels’ model errors and relatively accurate observations at these higher altitudes. To correct for these catastrophic effects, observations above 30 km have been removed from the assimilation system. This has resulted in a less significant reduction of the model bias as compared with the earlier experiments, but in an increase of the anomaly correlation scores for the 200-hPa temperature in the northern extratropics. As compared to the trial without GPS RO, a general improvement in anomaly correlation and bias scores is found. Once the unrealistic high-level structures have been corrected for, only the assimilation of bending angles is performing slightly worse than the control trial in the higher latitudes.

The effects of not using the high-level observations have been found to be more significant when observations of refractivity are used instead of bending angle. It is not clear why the differences between REFP and REF should be larger than the differences between BNDP and BND. One possibility is that the larger increments obtained at the top of the model, when all of the observations are assimilated, propagate to the lower levels in a lower number of assimilation cycles in the case of refractivity. The fact that the observation
increments of bending angle show higher vertical frequency variance than with the use of refractivity might make the propagation of the higher-level observation increments to the lower levels difficult. From the early results presented here, the assimilation of refractivities is performing better than the assimilation of bending angles.

Based on these early experiments with the assimilation of profiles of refractivity and bending angle, future work at NCEP/EMC will be focused on analyzing the benefits of the GPS RO with the latest version of the GSI (in its full horizontal resolution) in order to incorporate the COSMIC data in operations. The use of a larger amount of GPS RO data with COSMIC might affect the results presented in this study, and a further comparison between the assimilation of refractivity versus bending angle will need to be investigated. In the near future, we also plan to evaluate more sophisticated forward operators to account, at least partially, for the effects of the horizontal gradient of refractivity.

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