Operational Implementation of COSMIC Observations into NCEP’s Global Data Assimilation System

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ABSTRACT

The next generation of NCEP’s Global Data Assimilation System became operational on 1 May 2007. This system incorporates the assimilation of global positioning system (GPS) radio occultation (RO) profiles from the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) mission launched in April 2006. Roughly 1 yr after the launch of COSMIC, NCEP has begun operational use of this new dataset.

A preliminary assessment of this observation type was performed with an earlier version of NCEP’s analysis at a lower resolution. These experiments showed positive impact when GPS RO soundings from the Challenging Minisatellite Payload (CHAMP) mission were assimilated into the system in non–real time. In these earlier studies, two different forward operators for the GPS RO profiles were evaluated: one for refractivity and another one for bending angle.

In this paper, the data assimilation experiments with COSMIC observations that led NOAA/NCEP to assimilate COSMIC data into operations are described. The experiments were conducted with the current operational version of the code and at full operational resolution. Based on the results of the experiments analyzed here, profiles of refractivity were selected as the type of GPS RO observation to be assimilated. Further enhancement to the assimilation of bending angles is currently being evaluated at NCEP.

The results show a significant improvement of the anomaly correlation skill and a global reduction of the NCEP model bias and root-mean-square errors when COSMIC observations are assimilated into the system. The improvement is found for the temperature, geopotential heights, and moisture variables. Larger benefits are found in the Southern Hemisphere extratropics, although a significant positive impact is also found in the Northern Hemisphere extratropics and the tropics. Even if GPS RO observations cannot produce direct impact on the wind field through the adjoint of the forward operator, a slight benefit is found in the wind components.

1. Introduction

In April 2006, the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) mission (a joint project between the United States and Taiwan) launched six low-earth orbit (LEO) satellites into a circular polar orbit from Vandenberg Air Force Base, California (Anthes et al. 2000; Cheng et al. 2006). Each of the LEO satellites carries a global positioning system (GPS) radio occultation (RO) receiver to measure time delays of the GPS signals traveling from the GPS to the LEO satellites. As a GPS satellite occults behind the earth’s atmosphere, one can retrieve accurate information (sub-Kelvin temperature accuracy between ~5 and 30 km) on the thermodynamic state of the atmosphere traversed by the ray path (Kursinski et al. 1997; Rocken et al. 1997). To derive useful atmospheric information from time delay measurements, several processing steps and assumptions are usually made (see, e.g., Hajj et al. 2002; Kuo et al. 2004).

Over the past few years, the National Centers for Environmental Prediction’s Environmental Modeling Center (NCEP/EMC) has developed a new Global Data Assimilation System. This system includes the
capability to assimilate two different forms of GPS RO-retrieved observations. The first type of data is the bending angle, the change in the ray-path direction accumulated along the ray path due to the gradient of refractivity perpendicular to the trajectory of the ray. The second type of derived observation is the refractivity, which in the neutral atmosphere at the GPS frequencies (microwave range) is a function of temperature, water vapor pressure, and pressure. Soundings of refractivity are derived from soundings of bending angle after several assumptions and processing steps (Kursinski et al. 1997).

With the implementation of the new NCEP Global Data Assimilation System on 1 May 2007 into operations, the assimilation of GPS RO observations from the COSMIC mission became operational at NCEP. Unlike the European Centre for Medium-Range Weather Forecasts (ECMWF), observations from both rising and setting occultations are assimilated and there is no rejection of the observations with a height <4 km from the assimilation system, provided they pass the quality control checks.

A significant amount of research has been conducted in the last decade to show the potential impact of the GPS RO observations in numerical weather prediction (Liu et al. 2001; Poli and Joiner 2003; Zou et al. 2004; Wee and Kuo 2004; Cucurull et al. 2006). In addition, numerical weather prediction centers have developed and implemented different strategies to assimilate GPS RO data into their operational assimilation models (Healy et al. 2005; Healy and Thépaut 2006). Early studies at NCEP/EMC used data from the Challenging Minisatellite Payload (CHAMP) mission (Wickert et al. 2001) that was available in non–real time at the National Oceanic and Atmospheric Administration (NOAA; Cucurull et al. 2007a,b). The fact that both the CHAMP and COSMIC missions share similar GPS RO receiver technology allowed us to tune the system prior to the launch of COSMIC. These preliminary impact experiments showed the potential benefit of the GPS RO observations in improving analyses and forecasts. However, these early trials made use of an earlier version of NCEP’s analysis system at a lower resolution. The differing amounts of observations provided by COSMIC (six LEO satellites) and CHAMP (one LEO satellite) might also modify the results when assimilating COSMIC data instead of CHAMP data. Exploring the impact of higher analysis and forecast model resolutions and larger numbers of observations were necessary steps taken to justify the use of GPS RO operationally.

In this paper, the current operational code at operational resolution is used for the first time. The impact of COSMIC on top of the observations being routinely assimilated is evaluated and the forward operator selected for implementation in operations is described. This is the first time that NCEP’s operational assimilation system has been used to evaluate the impact of the assimilation of GPS RO observations from the COSMIC mission. Based on the results presented here, NCEP began operationally assimilating COSMIC data on 1 May 2007.

The paper is arranged as follows: section 2 reviews the different forward operators tested at NCEP/EMC to assimilate GPS RO observations, and the selected operator is justified in section 3. The different impact experiments are analyzed in section 4. Finally, a summary is provided in section 5.

2. Methodology

Over the past few years, NCEP/EMC has developed two different strategies to effectively assimilate GPS RO observations into NCEP’s model. The first forward operator simulates observations of refractivity (N) as a function of the geometric height, and it is computed from model variables of temperature, pressure, and water vapor pressure as follows (Smith and Weintraub 1953):

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

where \( P \) is the total atmospheric pressure (in hPa), \( T \) is the atmospheric temperature (K), and \( \varrho_v \) is the partial pressure of water vapor (hPa).

The second approach simulates observations of bending angle (\( \alpha \)) as a function of the asymptote miss distance (or “impact parameter”) \( a \). The forward operator to compute bending angles from model variables requires the evaluation of a nontrivial integral:

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

where \( n \) is the index of refraction of the atmosphere and \( r \) is the radius of a point on the trajectory of the ray. The magnitude \( x \) is the refractive radius. The miss distance \( a \) remains constant along the trajectory of a ray for a spherically symmetric atmosphere.

A detailed description of the implementation, evaluation, and testing of both forward operators at NCEP/EMC can be found in Cucurull et al. (2007a,b). Note that the quality control procedures and error characterizations have been developed separately for both forward operators. It is also important to remark that in the current design of both forward operators, the ef-
fects of the horizontal gradients of refractivity have been neglected and the assumption of the spherical symmetry of the atmosphere is implicit when assimilating profiles of refractivity and bending angle.

In the GPS radio occultation processing technique, profiles of $N$ are derived from profiles of $\alpha$ under the assumption of spherical symmetry of the atmosphere. The same assumption is used when deriving bending angles from GPS raw measurements. However, the effects of neglecting the horizontal gradient component are small in the derivation of $\alpha$ but are much more significant in the retrieval of $N$ (Kursinski et al. 1997). This along with the fact that some auxiliary meteorological information is necessary in order to obtain refractivities from bending angles makes the use of the bending angle more desirable for assimilation than the use of refractivities. On the other hand, the larger variability of $\alpha$ due to vertical refractivity gradients makes its assimilation more challenging. In the modeling counterpart, the procedure is reversed; that is, profiles of the bending angle are derived from simulated profiles of the refractivity.

The refractivity and bending angle forward operators were implemented in the Grid-point Statistical Interpolation (GSI) analysis code (Wu et al. 2002). For each forward operator, the tangent-linear and adjoint codes with respect to the analysis variables of surface pressure, virtual temperature, and specific humidity were developed, tested, and implemented in the analysis algorithm. The observational error covariance matrix for the GPS RO data is assumed diagonal, thus neglecting correlations between different observations. The GSI code is coupled with the NCEP Global Forecast System (GFS) and has replaced the NCEP Spectral Statistical Interpolation (SSI) global analysis system (Derber et al. 1991) operationally starting on 1 May 2007. The background error covariance matrix is used to precondition the minimization problem. This preconditioning is equivalent to the redefinition of the control vectors using the square root of the background error covariance matrix (Derber and Rosati 1989).

3. Selection of a forward operator

Three experiments for a two-month period were run in order to evaluate the impact of the assimilation of COSMIC observations and select a forward operator to be implemented in operations. In a control experiment, the GSI–GFS was run without the COSMIC data. In two additional experiments, observations of the bending angle and refractivity were also assimilated, respectively. All three experiments made use of an earlier version of the analysis system. In the experiments including COSMIC, GPS RO observations above 30 km were rejected in order to avoid unrealistic increments in the higher model levels (Cucurull et al. 2007b).

Based on the results of these experiments, the anomaly correlation scores as a function of the forecast length for the 500-hPa geopotential heights showed a clear degradation in the Southern Hemisphere (SH) extratropics when compared to the control when bending angles were assimilated. On the other hand, NCEP’s model skill improved with the use of COSMIC refractivities. Even if the experiments with COSMIC data indicated a neutral impact in the Northern Hemisphere (NH) extratropics, the degradation in the SH extratropics with the use of bending angles (with the current quality control algorithm and error characterization) was significant. Similar results were found for other variables and at other levels. As a result, the use of refractivity was selected for operational implementation at NCEP.

It is not clear why scores should degrade with the use of bending angles and improve with refractivity. One would expect similar or better results with the use of less-processed observations. Actually, earlier trials did not show significant differences between both forward operators and the NCEP’s model skill improved when GPS RO observations were added into the assimilation system, regardless of the type of observation being used. As the quality control and error characteristics were tuned differently for each forward operator, it is possible that the use of the bending angle with a higher-resolution forecast model and with the larger number of observations available from COSMIC may require further tuning than when using refractivity. Another possibility is that the structures in the background error covariance matrix do not represent correctly the vertical structures of the bending angle in the operational analysis code. Finally, as the processing of the GPS RO observations has been changed since the earlier experiments, it is possible that the software upgrades have affected the nature of the profiles of the bending angle more. The tuning of the system to improve the model skill when assimilating soundings of the bending angle is a subject of ongoing research at NCEP/EMC and we expect to assimilate bending angles operationally in the near future.

4. Assimilation experiments

Once the forward operator for refractivity was selected for implementation in operations, two 1-month experiments were run in order to fully evaluate the impact of refractivities on top of the assimilation of current conventional and satellite observations. The tri-
als were run on the operational machine with the same code that went into operations at NCEP on 1 May 2007. Due to the limitation of computer resources, an experiment with bending angles was not conducted. Experiments PRYnc (control, with conventional and satellite observations) and PRYc (adding COSMIC refractivities on top of the current observations) ran from 24 October 2006 to 30 November 2006.

Soundings of refractivity as a function of the geometric height, and of bending angle as a function of the impact parameter, are routinely provided by the University Corporation for Atmospheric Research (UCAR) COSMIC Data Analysis and Archival Center (CDAAC) in binary universal format for data representation (BUFR) format. Each profile has 200 levels in the vertical, ranging from near the surface to around 40-km height. As the impact of COSMIC needs to be evaluated within an operational framework, only those profiles that arrived with latency less than the cutoff time in the assimilation system were used. The GSI analysis has an assimilation window of ±3 h and runs with two different cutoff times. An early analysis is run with a cutoff time of less than 3 h and is used to initialize the GFS forecasts. Short forecasts from a later GSI analysis (cutoff time of ~6 h) provide the background field for the next analysis cycle. The number of GPS RO profiles assimilated in the early analysis was ~1000 per day. The skill levels of the PRYnc and PRYc experiments are evaluated on different fields for November 2006.

a. Mass fields

The anomaly correlation (AC) score as a function of the forecast length for the temperature field at 200 hPa is shown in Figs. 1a–c for the NH extratropics, the tropics, and the SH extratropics, respectively. Each experiment is verified against its own analysis. As can be seen in the figure, the use of COSMIC refractivities globally increases the AC skill. The impact of COSMIC is found to be more significant in the tropics, where we gain ~half a day at day 5, although there is a slight degradation around day 1. As the forecast skill recovers quickly after day 1, this degradation might be due to a sampling error. The benefits of the GPS RO data are also significant in the extratropics (Figs. 1a and 1c),
being more significant in the SH extratropics (gain of ~6 h at day 6). In the SH (NH) extratropics, the differences between PRYc and PRYnc are statistically significant at the 21% (18%) level at day 4 when calculated with a Student’s t test. In general, the differences between PRYnc and PRYc are larger in the tropics and in the SH extratropics than in the NH extratropics, probably because the density of the conventional observations is lower.

In terms of biases and rms errors, the verification of the model forecasts against their own analyses shows a reduction of the NCEP’s model bias in the extratropics when COSMIC data are assimilated into the system. This is shown in Figs. 2a and 2b where the mean difference and rms errors for the temperature at 200 hPa as a function of the forecast length are presented for the NH and SH extratropics, respectively. Even if there is not a noticeable reduction of the rms error, there is a significant reduction of the forecast model bias in the extratropics in PRYc as compared to PRYnc [a reduction of 0.15 (0.18) K in the NH (SH) extratropics at day 5]. In the tropical latitudes (not shown), there is little difference between the experiments in either rms or bias.

The verification against radiosonde observations (not shown) also indicates a reduction of the NCEP’s model temperature bias in the middle and upper troposphere in PRYc, as compared to PRYnc. The fit to the observations also shows a reduction of the rms error in the SH extratropics when COSMIC observations are assimilated into the system (PRYc). The benefits of using COSMIC in improving the fit to the observations extend to the stratosphere, where the rms errors are also reduced.

Scores for the tropical latitudes are mainly driven by the forecast model characteristics due to the lower number of conventional observations available for assimilation and the weaker mass–wind coupling. Along with the fact that thermodynamic processes are more complex to model in these lower latitudes, this results in a lost of accuracy in numerical weather prediction models in the tropics, as compared to other latitudes. As a consequence, the AC scores in the tropics might increase or decrease depending on the analysis being used to verify the forecasts. To evaluate the impact of the COSMIC observations in the tropics, it would be desirable to evaluate the scores of the forecasts of
experiments PRYnc and PRYc in terms of an independent analysis. This is partially accounted for in Figs. 3a–c for the 300-, 200-, and 100-hPa pressure levels, respectively. Figure 3 shows the AC scores for the temperature field in the tropics as a function of the forecast length, where the forecasts have been verified against a common analysis. This analysis is a consensus between the NCEP, U.K. Met Office and ECMWF analyses, thus partially removing the effect of the NCEP analysis in the verification of the PRYnc and PRYc forecasts. Figure 3b needs to be compared with the results shown in Fig. 1b, while there are no counterparts for Figs. 3a (300 Pa) and Figs. 3c (100 hPa). The first noticeable characteristic in Fig. 3b is the significant decrease in tropical AC scores as compared to Fig. 1b. This reflects the increased sensitivity of the AC scores in the tropics to the differences in the three analyses (NCEP, Met Office, and ECMWF) at these lower latitudes. Similar plots for the NH and SH extratropics show better agreement with no significant drop in AC scores. Another important pattern in Fig. 3b as compared to Fig. 1b is the larger difference between the results from experiments PRYnc and PRYc in the short- and medium-range forecasts. It is important to remark that the NCEP analysis used to build the consensus analysis does not contain GPS RO data. Thus, the fact that the benefits from COSMIC (PRYc over PRYnc) are larger when the forecasts are verified against the consensus analysis implies that the gain in AC score in PRYc over PRYnc is larger than Fig. 1b would seem to indicate. Benefits from the assimilation of COSMIC data are evident at short-range forecasts (less than 1 day) and extend to higher levels (Fig. 3c). Larger differences between PRYc and PRYnc when model forecasts are verified against the consensus analysis are also found at other pressure levels. The differences between PRYc and PRYnc, when verified against the common analysis, are statistically significant at the 22% (12%) level at 300 (100) hPa for day 3 when calculated with a Student’s t test. Also, note that the slight degradation found around day 1 in Fig. 1b has been removed in Fig. 3b (there is rather a slight improvement in PRYc over PRYnc).

The benefits of the assimilation of COSMIC refractivities are also found at other levels and for other variables. The AC scores for the geopotential heights at 1000 and 500 hPa as a function of the forecast length are shown in Figs. 4 and 5, respectively. In each figure, scores for the (a) NH and (b) SH extratropics are presented. For both pressure levels, the increase in AC skill in PRYc over PRYnc is more significant in the SH extratropics (Figs. 4b and 5b), where the benefits of COSMIC are already noticeable at short-range fore-

![Fig. 3. Same as Fig. 1, but for (a) 300, (b) 200, and (c) 100 hPa in the tropics. The analyses used for verification are a consensus between the NCEP, Met Office, and ECMWF analyses.](image)
casts (~day 2) and increase at medium-range forecasts (~half a day at day 6). The impact of COSMIC in the NH extratropics is less significant than in the SH latitudes but the results are still quite impressive due to the large number of observations already available for assimilation. At 1000 hPa, the impact of COSMIC in the NH extratropics is appreciable starting around day 4 and its largest benefit is found at day 7. Similar results are found at 500 hPa. The differences between PRYc and PRYnc are statistically significant at the 3% level for day 5 in the NH extratropics (at 1000 and 500 hPa), when calculated with the Student’s t test. In the SH extratropics, the differences at day 3 are statistically significant at the 3% (2%) level at 1000 (500) hPa. Improvements in the AC scores for the geopotential heights are also found at other pressure levels. Once again and for the period being evaluated, the impact is more significant in the SH extratropics than in the NH extratropics.

b. Tropical winds

GPS RO observations do not contain direct information on the wind field, meaning that we will not obtain wind increments in the analysis through the adjoint of the forward operator for refractivity (or bending angle) described in Eq. (1). The increments for the wind components due to the GPS RO data, if any, should come through the dynamics of the model and the balance constraints in the analysis system. In general, we found

Fig. 4. The AC scores (PRYnc and PRYc) for the 1000-hPa geopotential heights in the (a) NH (20°–80°N) and (b) SH (20°–80°S) extratropics as a function of the forecast length. The results are filtered to represent the structures with total wave-numbers 1–20.

Fig. 5. Same as in Fig. 4 but at 500 hPa.
neutral or slightly positive impacts for the high-level wind components when COSMIC was included in the assimilation system. This can be seen in Fig. 6, where the 200-hPa time series of the rms errors for the wind vector at day 2 are displayed for experiments PRYc and PRYnc. The verification is done against the consensus analysis discussed above. (Verification against our own analysis shows a neutral impact for COSMIC.) The impact of COSMIC on the low-level wind was found to be neutral for the period being tested.

c. Humidity

A positive impact was also found on the moisture field in PRYc, when compared to PRYnc. The impact may be primarily from the previously shown improvement to the mass and wind fields. The forward operator for refractivity described in section 2 is very sensitive to the humidity content of the atmosphere. The contribution of the wet term to the total refractivity in Eq. (1) largely varies with the amount of moisture in the atmosphere and it can dominate the vertical gradients of refractivity in the lower tropical troposphere (Kursinski et al. 1997). The impact of COSMIC observations on the mean differences and rms errors for the specific humidity at 850 hPa is shown in Figs. 7a–c for the NH extratropics, the tropics, and the SH extratropics, respectively. A slight reduction of the bias is found in the NH extratropics (Fig. 7a). The impact of COSMIC is more significant in the tropics (Fig. 7b) and the larger improvement is found in the SH extratropics (Fig. 7c), where PRYc also slightly reduces the rms error. In the SH extratropics, the correction of the NCEP model bias in PRYc extends to other vertical levels analyzed in this study.

5. Conclusions

After developing the infrastructure necessary to assimilate GPS RO observations, NCEP began to use COSMIC data operationally on 1 May 2007, along with the implementation of a new Global Data Assimilation System. Profiles of refractivity were chosen for implementation, while the tuning of the assimilation of bending angles with the current version of the code is being finalized at NCEP/EMC.

In this study, some of the impactful results of COSMIC on several fields and at different vertical levels have been presented. For the period analyzed here, the gain obtained with the assimilation of COSMIC data has been found to be significant. In general, we should expect the results to be sensitive to the synoptic atmospheric situation, model performance, and location of the GPS RO and other observations. When including a new instrument operationally in a numerical weather prediction model, one would expect the new data to provide a neutral or positive impact. The promising results found with COSMIC seems to indicate that the GPS RO observations provide a unique and valuable piece of information to the assimilation system. However, improvement of the forward operators and the use of less processed observations are preferred to fully exploit the information contained in this new dataset.

Following the results presented in this study, NCEP/
EMC made the decision to include COSMIC in its new Global Data Assimilation System, just 1 yr after the launch of the satellites. Future work at NCEP/EMC will include further tuning of the quality control checks, enhancing the performance of the assimilation of bending angles, and partially accounting for horizontal gradients of refractivity in the design of the forward operator.

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Fig. 7. The (left) rms and (right) mean differences (g kg⁻¹) for the specific humidity at 850 hPa (PRYnc and PRYc) in the (a) NH extratropics (20°–80°N), (b) tropics (20°S–20°N), and (c) SH extratropics (20°–80°S).
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