Impact of 837 GPS/MET bending angle profiles on assimilation and forecasts for the period June 20–30, 1995

Hui Liu, 1 X. Zou, 1 H. Shao, 1 R. A. Anthes, 2 J. C. Chang, 3 J.-H. Tseng, 3 and B. Wang 4

Abstract. With a ray-tracing procedure and variational data assimilation techniques, it is now possible to make direct use of radio occultation bending angles, rather than their derived temperature and moisture retrievals, in atmospheric data analysis and assimilation. This paper describes results obtained from including more than 800 GPS/MET bending angle profiles, available over an 11-day period, 20–30 June 1995, into the National Centers for Environmental Prediction spectral statistical interpolation analyses. The methodology for assimilating the bending angles (including an impact parameter offset correction) is briefly summarized. Verified with 56 collocated radiosonde profiles, the assimilation of only GPS/MET bending angles improves the temperature and specific humidity analysis above 850 mbar. Even though the number of GPS/MET soundings is still far less than conventional data and operational satellite soundings, our results from two continuous 11-day data assimilation cycles demonstrate a closer fit of both GPS/MET and conventional observations to the analyses between 850 and 200 hPa when the bending angles are incorporated. Including the bending angles also results in a small but consistent improvement in the short-range (6 hours) and medium-range (1–5 days) forecast skills, especially in the Southern Hemisphere.

1. Introduction

As shown by the Global Positioning System Meteorology (GPS/MET) experiment [Kursinski et al., 1996; Ware et al., 1996], the availability of Global Positioning System (GPS) satellites and the development of GPS receivers carried on a Low Earth Orbiting (LEO) satellite create an opportunity for active remote sounding of the Earth’s atmosphere by radio occultation technology. Phase delay measurements of GPS radio signals as they are occulted by Earth’s atmosphere depend on the atmospheric refractivity, which is determined by the atmospheric temperature and humidity distributions. Atmospheric profiles of bending angle and refractivity can be provided globally in all weather conditions. At temperatures below 250 K (above 5–7 km), where the effects of water vapor are negligible, vertical profiles of temperature (dry-temperature retrieval), density, and geopotential height may be obtained using the GPS limb-sounding technique. At temperatures above 250 K in the troposphere (below 5–7 km) the contribution of water vapor to the refractivity is significant, and the accuracy of the dry temperature retrieval (which assumes water vapor is negligible) is degraded [Ware et al., 1996; Kursinski et al., 1996, 1997]. It is generally impossible to compute both temperature and moisture variables from an occultation sounding using a traditional retrieval method, an underdetermined problem. Because of this limitation, and the limited penetration of the majority of GPS/MET soundings in the lower troposphere caused partly by the relatively low gain antenna used for the GPS/MET proof-of-concept instrument, initial results of radio occultation observations from GPS/MET have been reported mostly above 5–7 km and for dry temperature retrievals [Rocken et al., 1997].

Over the past few years the Florida State University, and UCAR team, has been developing methods to assimilate GPS/MET bending angles. A forward observation operator, which transforms the analysis variables into bending angles, and other related operators (such as the adjoint of the ray-tracing model) needed for the direct use of the bending angles were developed and tested [Zou et al., 1999]. These bending angle operators were then linked to the National Centers for Environmental Prediction (NCEP) spectral statistical interpolation (SSI) analysis system. Some issues associated with the use of radio occultation data were addressed using a total of 30 GPS/MET soundings in the work of Zou et al. [2000]. For example, it was shown that the mixed use of bending angles and refractivities produced an analysis result similar to the one using just bending angles, while the computational cost was much reduced.

The development of the bending angle and refractivity assimilation system [Zou et al., 1999, 2000] and the availability of many GPS/MET soundings, which reached relatively low altitudes in the troposphere during June 1995, provide an opportunity to examine the potential forecast impact of GPS occultation measurements. A close examination of the GPS/MET data in the lower troposphere may also provide insight into the quality of the data, which were obtained from a relatively primitive technology.

This paper tests the performance of the GPS/MET bending angle assimilation by examining the impact of GPS/MET bending angle measurements on analysis, and short-range (6 hours) and medium-range (1–5 days) forecasts during an 11-day pe-
period. We use the bending angle data assimilation system developed by Zou et al. [2000]. A total of 837 GPS/MET occultations available during June 20–30, 1995, are assimilated into the global NCEP analyses, along with conventional observations (consisting of mainly radiosonde, surface, aircraft, satellite wind retrieval, and dropsonde data). The total number of conventional observations during this 11-day period is on the order of $10^5$–$10^6$. Section 2 describes the GPS/MET bending angle observations, and the collocated radiosonde stations. The NCEP 3D-Var system and the experiment design of two
2. GPS/MET Observations

The GPS/MET observations during June 20–30, 1995, are chosen in this study for the following reasons: (1) They are within one of the four "prime times" during which antispoofing (A/S) was turned off and the carrier phase can be measured with higher precision and accuracy than when A/S is turned on; (2) a relatively large number of soundings penetrated to low altitudes in the troposphere; and (3) both the total number of occultations and those that were processed are relatively high [see Rocken et al., 2000, Figure 2]. Figure 1a shows the distribution of the 837 GPS/MET occultation profiles available during this 11-day period. More than half of the 837 soundings are located over the data-sparse oceanic regions. Of these 837 GPS/MET soundings, there are 52 for which there is at least one radiosonde profile that had more than five levels of data and was observed within a ±3-hour time window and 200-km distance. The total number of the radiosonde profiles collocated with the GPS/MET occultations is 56. The locations of these 52 GPS/MET soundings and 56 radiosonde profiles are shown in Figure 1b. Only 7 out of the 56 radiosonde stations are located in the Southern Hemisphere. Therefore the validation data sets from these 56 radiosondes will be geographically inhomogeneous.

Figure 1. (a) Distribution of the number of GPS/MET observed soundings with (a) height and (b) latitude during 20–30 June 1995. In Figure 2b, the gray bars include all GPS/MET soundings and the solid bars are the numbers of the soundings which have at least one conventional observation within a distance of 400 km. The total number of soundings are 522 (solid bars) and 837 (gray bars).
Figure 4. Vertical profiles of $q_{\text{guess}} - q_{\text{sonde}}$ (solid), $q_{\text{assim without}} - q_{\text{radiosonde}}$ (dotted), and $q_{\text{assim with}} - q_{\text{radiosonde}}$ (dashed), where $q_{\text{guess}}$ is from the NCEP background without GPS/MET data assimilation, $q_{\text{sonde}}$ is the radiosonde observations at (144.38°W, 27.62°S) at 0000 UTC, June 29, 1995, $q_{\text{assim without}}$ is the results from GPS/MET bending angle assimilation without the impact parameter offset correction, and $q_{\text{assim with}}$ is the results from GPS/MET bending angle assimilation with the impact parameter offset correction. The GPS/MET occultation assimilated is located at (144°W, 27°S), which was observed at 2312 UTC, June 28, 1995. The distance between the GPS/MET occultation and the radiosonde sounding is 178 km.

There are more than 200 GPS/MET soundings that penetrated to 200 m or lower (Figure 2a). About half of the soundings (403) reached a height as low as 1 km. The number of GPS/MET observations increases with height from about 250 at 0.2 km to about 700 at 2.5 km and becomes relatively constant above 2.5 km. Figure 2b shows the latitudinal distribution of the number of GPS/MET observations during this period. There are more GPS/MET data between 40°N–70°N and 10°S–40°S than in other latitudinal bands, very little data between 80°N and 90°N, and no data between 70°S and 90°S.

High vertical resolution is a characteristic of radio occultation data. For neutral atmospheric soundings, the GPS/MET instrument measures the Doppler-shifted frequency every $2 \times 10^{-2}$ s (50 Hz) during a typical occultation event. Such a sampling rate results in a 25-m vertical resolution for an idealized symmetric atmosphere where the refractivity decreases exponentially. However, because of the system measurement errors, diffraction, and horizontal gradients of refractivity, the actual vertical resolution is about 0.1–0.5 km in the lower troposphere and 1.5 km in the stratosphere [Melborne et al., 1994].

The bending angle observations used for this study are obtained from the GPS/MET Level-3 data provided by the UCAR Payload Operations Control Center (http://cosmic.cosmic.ucar.edu/gpsmet). They were produced through several data processing steps as described by Rocken et al. [1997]. The bending angle and impact parameter are not directly measured quantities. They are derived from the Doppler shift measurements at two frequencies (1227.6 and 1575.42 MHz). The use of the spherical symmetry assumption results in a constant impact parameter ($a_{\text{gps}}$) along the ray path. For calculation of the impact parameter in GPS/MET, the center of the sphere is put into the local curvature center of the reference ellipsoid under the estimated tangent point of the lowest ray. The tangent point altitudes ($z_{\text{gps}}$) are converted from impact parameters after an Abel inversion using the formula $a_{\text{gps}} = n(z_{\text{gps}} + r_{\text{loc}})$, where $n$ is the refractive index at the tangent point and $r_{\text{loc}}$ is the radius of local curvature of the actual Earth of the observed occultation. A unique pair of a bending angle and an impact parameter ($a_{\text{gps}}, a_{\text{gps}}$) can be deduced from the two signals used by GPS at each measuring time through a linear combination of the bending angles at the two frequencies [Vorob’ev and Krasil’nikova, 1994]. The tangent point position, tangent direction of the ray at the tangent point, and the unit vector normal to the occultation plane at the tangent point are also provided in the GPS/MET Level-3 data file. Since the spherical symmetry assumption is violated by the existence of horizontal gradients of refractivity in the atmosphere, the actual impact parameter is not constant along the ray, and the bending angle derived from GPS measurement is not the true bending angle. We shall call $a_{\text{gps}}$ the "pseudo" bending angle.

A diffraction correction [Gorbunov and Gurvich, 1998] was applied to reduce the effect of multipath propagation caused by the complicated structure of the humidity field in the low
troposphere and to remove ambiguities of the bending angle as a function of height. The ionospheric effect on the bending angle is removed by means of using a dual-frequency technique [Vorob'ev and Krasil'nikova, 1994].

3. Data Assimilation Experiments: Cost Function Formulation, Forward Modeling and Experiment Design

The NCEP SSI analysis system [Parrish and Derber, 1992; Derber and Wu, 1998] is used for this study. A description of the use of GPS/MET bending angle and refractivity data in a prototype NCEP SSI analysis and assimilation system was provided by Zou et al. [2000]. The SSI analysis system produces an analysis through the minimization of an objective function, which consists of three terms: a weighted square of the background increments $(x - \bar{x})$, a weighted square of the observational increments $(y - \bar{y})$, and a weighted square of the divergence tendency increments $(\partial D/\partial t - \partial D_\theta/\partial t)$; that is,

$$J(x_a) = \frac{1}{2} (x_a - \bar{x})^T B_a^{-1} (x_a - \bar{x}) + \frac{1}{2} (H(x_a) - y_{obs})^T R^{-1} (H(x_a) - y_{obs}) + \left( \frac{\partial D}{\partial t} - \frac{\partial D_\theta}{\partial t} \right)^T O_D^{-1},$$

where $x_a$ is a vector of analysis variables in the spectral space, including the vorticity ($\zeta$), the unbalanced part of the divergence, the unbalanced temperature, the logarithm of the unbalanced surface pressure, and the water vapor mixing ratio, $x_b$ is a 6-hour forecast from the previous cycle of analysis (also}

Figure 5. Mean errors and the RMS errors of the temperature and specific humidity fields before (solid line) and after (dotted line) the assimilation of only GPS/MET bending angles for the 52 single-occultation experiments, verified with collocated radiosonde observations.
known as the background or first guess), and $y_{\text{obs}}$ is a vector of observations. $B_0$ is a diagonal background error covariance matrix of $x_b$, $R$ is an observational error covariance matrix, $H$ is an observation operator that converts the analysis variables on model grids to the observation quantities and locations, $D$ is a vector of the spectral coefficient of divergence, and $O_b$ is a diagonal background error covariance matrix of the background divergence $D_b$. The third term in (1) imposes an additional dynamical constraint (the time tendency of the divergence to be small) to increase the balance in the analysis increment. The dimensions of the vectors $x_b$ and $y_{\text{obs}}$ are on the orders of $10^5$ and $10^7$, respectively. The NCEP global model has 28 vertical layers, extending from the Earth's surface to a height of about 35 km. We have chosen a vertical resolution of 0.4 km for the forward ray-tracing model, which is comparable to the vertical resolution of the NCEP model in the lower troposphere.

The weightings for the observations are simply defined as the inverse of the mean square differences between the observed and the modeled bending angles based on the NCEP
Figure 7. Vertical profiles of the mean errors of bending angle for (a) NOGPS and (b) BOTH. All bending angles from the 837 GPS/MET occultations are included in the calculation. Solid line, background; dotted line, analysis.

background field using all the GPS/MET data available during the 11-day period, 20–30 June 1995. These differences contain a contribution of errors from the background fields. The estimated standard deviation values of the bending angle errors from such an approximation is shown in Figure 3. Compared to a theoretical estimate used by Palmer et al. [2000], the values in Figure 3 are close to the values assumed by Palmer et al. below 20 km. However, they are much larger than those of Palmer et al. above 20 km. Sensitivity of the assimilation results to the use of differently estimated bending angle observational error variances, including those used in this study, the ones estimated on the basis of three-dimensional (3-D) and 2-D ray-tracing simulations [Zou et al., 2001], and those of Palmer et al. will be reported in future papers.

The observation operator for bending angles used in this study is a 2-D ray-tracing model developed by Gorbunov et al. [1996]. Its application in a variational analysis system was described by Zou et al. [1999, 2000]. In this model the ray-tracing is carried out in a 2-D occultation plane, which contains the tangent point and is perpendicular to the normal direction of the GPS/MET sounding at the tangent point. Therefore the perpendicular gradient of refractivity is neglected. The unit vector normal to the occultation plane and the tangent point position provided by the GPS/MET Level-3 data are used as inputs to the 2-D ray-tracing model to obtain a virtual GPS satellite position and the initial tangent direction of the ray. Then, the ray equations are integrated, starting from the virtual point using the alternating direction implicit method. A fixed step size of 30 km is used for the ray integration. The atmospheric layer described by the NCEP model is placed on a sphere where the radius is calculated as the local curvature radius at the GPS/MET sounding location. The ray tracing continues until the ray goes out of the atmosphere, which is assumed to be at a distance of more than 100 km from the Earth’s surface (the value of 100 km for the ray integration range is chosen to be large enough to ensure the accuracy of the bending angle simulation but small enough to save computing time). The position and the tangent direction of the ray at the ending point of the simulated ray are taken as those at the LEO satellite. The bending angle of the ray is calculated by the angle between the two tangent directions at the starting and ending points of the ray. Currently, attempts are not made
Table 1. Temperature and Specific Humidity Errors Before and After Assimilation of 52 GPS/MET Occultation Profiles

<table>
<thead>
<tr>
<th>Assimilation</th>
<th>Temperature, °C</th>
<th>Specific Humidity, g kg(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>RMS</td>
</tr>
<tr>
<td>Before</td>
<td>0.3</td>
<td>1.8</td>
</tr>
<tr>
<td>After</td>
<td>0.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The radiosonde observations above 850 mbar at the 56 radiosonde stations collocated with the assimilated GPS/MET occultations are used for the evaluation of GPS/MET bending angle assimilation results.

to calculate the same "pseudo" bending angle that is calculated from the observations. Instead, the modeled bending angle is taken as a function of the impact parameter at the tangent point \(\alpha_{\text{model}}(a_t)\), where the subscript "\(t\)" refers to the tangent point. This vertical profile of the bending angle in terms of the impact parameter at the tangent point is then compared with the vertical profile of the "pseudo" bending angle \(\alpha_{\text{gps}}(a_{\text{gps}})\).

Each point in Figure 1a represents the average position of a vertical profile of the GPS/MET bending angle. A single bending angle or refractivity observation is a complicated function of atmospheric thermodynamic properties (temperature, water vapor, and pressure) along its ray path, reflecting an averaged effect of atmospheric refractivity near the tangent point within ±500 km distance [Melbourne et al., 1994; Anthes et al., 2000]. The incorporation of GPS/MET data through a ray-tracing procedure assimilating the bending angle observations automatically takes

Figure 8. Vertical profiles of the mean errors of (a) temperature and (b) specific humidity for NOGPS (solid line) and BOTH (dotted line). All of the conventional observations of temperature and specific humidity are included in the calculation.
such an averaging effect into account, which is in general not true in the assimilation of bending angle using forward Abel transform [Palmer et al., 2000] or the assimilation of GPS/MET refractivity without an averaged weighting operator.

To test the effectiveness of bending angle assimilation, single-sounding experiments are first conducted for the 52 GPS/MET occultations shown in Figure 1b, for which there are collocated radiosonde soundings as independent data sources for the evaluation of the bending angle assimilation results. Then, two 11-day data assimilation experiments in a cycling mode at a 6-hour interval are carried out, one with only conventional observations (NOGPS, which consists of mainly radiosonde, surface, aircraft, satellite, and dropsonde data) and the other with both the GPS/MET and the conventional observations (BOTH). The total number of conventional observations over the 11-day period is 1,559,218 for wind, 646,383 for temperature, 232,559 for moisture, and 310,803 for surface pressure. Analyses are produced at times \( t_t \) centered at 0000, 0600, 1200, and 1800 UTC each day. All the GPS/MET and conventional observations within \( t_t \pm 3 \) hours are included in the SSI experiment at time \( t_t \). The 6-hour model forecast starting from the previous analysis time \( t_t \) is used as the background field \( x_0 \) for the new analysis at the time \( t_{t+1} \). There are two outer loops (updates for the nonlinear model solution), each with 100 inner loops (the total number of iterations for updating the analysis increment within each outer loop). In another word, a total of 200 iterations are carried out at each analysis time. The minimization performed well, with a reduction of 6–7 orders of magnitudes of the norm of the gradient of the cost function.

4. Numerical Results
4.1. An Impact Parameter Offset Correction

Since the forward model does not exactly follow the procedure by which the GPS/MET bending angle is derived (see sections 2 and 3), an impact parameter offset correction is applied for the modeled bending angle profile. The following discussions outline the motivation and the implementation of this correction.

The bending angle depends on the gradients of refractivity, with the ray bending toward higher refractivity. At high altitudes (40–100 km) the bending is negligible and the impact parameter is nearly constant along the ray path. Therefore the
impact parameter at the tangent point height should be very close to the GPS-derived impact parameter at these heights. Any appreciable difference between the modeled and the GPS/MET-derived impact parameter at these high altitudes represents a measure of uncertainty in the impact parameter calculation between the forward model simulation and the GPS/MET data. This uncertainty can be removed from the forward modeling through a correction applied to the modeled bending angle vertical profile:

\[ \alpha_{\text{model}}(t) = \alpha_{\text{model}}^0(t) - \Delta a \],

where \( \alpha_{\text{model}}^0 \) is the original (uncorrected) value of the model bending angle, and \( \Delta a = a^{40\text{km}} - a_{\text{GPS}}^{40\text{km}} \) is the difference between the modeled and GPS/MET-derived impact parameters at the 40-km tangent height. The 40-km height chosen in (2) is near the 2-D model top where the highest ray for each occultation is found. The magnitude of \( \Delta a \) depends on the satellite geometry and the location of the occultation. Such an uncertainty in the model impact parameter for the assimilation of bending angle is caused by incompatibility between the GPS/MET Level-3 data processing and the 2-D simulation model of the Earth’s parameters. Therefore the values of \( \Delta a \) should be constant throughout the vertical profile. The average magnitude of \( \Delta a \) is about 526 m, with a standard deviation of 299 m. Such an impact parameter offset is larger than the uncertainty in the observed impact parameter. The latter is only several tens of meters [Healy, 2001; Zou et al., 2001].

Figure 4 shows the vertical profiles of temperature and specific humidity before and after GPS/MET data assimilation with and without the impact parameter offset correction. The GPS/MET occultation assimilated is located at (144°W, 27°S), which was observed at 23.12 UTC June 28, 1995. The impact parameter offset correction made to this occultation is 563 m. There was a collocated radiosonde sounding, whose distance to this GPS/MET occultation is only 178 km. Compared with the radiosonde observations, the temperature and specific humidity profiles after the bending angle assimilation without the impact parameter offset correction contain large errors. After incorporating the correction, these errors in the temperature and specific humidity analysis are largely removed.
4.2. Results From GPS/MET Single-Occultation Bending Angle Assimilation Experiments

To examine the general performance of the bending angle assimilation, a set of single-occultation experiments is conducted for all the 52 GPS/MET soundings shown in Figure 1b. The 56 vertical profiles of temperature and specific humidity from radiosondes, which are collocated with these GPS/MET occultations, are used as independent data sources to evaluate the results from the GPS/MET bending angle assimilation.

Figure 5 provides the mean errors and the root-mean-square (RMS) errors of the temperature and specific humidity fields before and after the GPS/MET bending angle assimilation. An overall improvement in the temperature and specific humidity analysis due to the use of GPS/MET bending angle is observed except for the moisture variable below 850 hPa.

To examine the problems associated with the moisture analysis in the lower troposphere below 850 hPa, we plotted the mean error and RMS error differences between the bending angle minimization solution and the background as a function of the radiosonde sounding number (Figure 6). The absolute value of the mean errors for the minimization solution and the background are differenced. A negative value in Figure 6a (mean error differences with and without GPS/MET bending angles) or Figure 6b (RMS error differences with and without GPS/MET bending angles) implies an error reduction after bending angle assimilation. The differences in the mean error (Figure 6a) and the RMS error (Figure 6b) of the two moisture analyses show more improvement than degradation through the GPS/MET bending angle assimilation. The degradation in the moisture analysis for most soundings (Figures 6a and 6b, top panels) is found to be dominated by the low-level moisture adjustments (Figures 6a and 6b, bottom panels). We mention that out of the 52 GPS/MET soundings assimilated, only about half reached below 850 hPa. Also, in the lower troposphere, both the observational and the forward modeling errors are largest. If we limit the analysis verification to above 850 hPa (statistically more significant), the improvement of moisture analysis through the assimilation of only GPS/MET bending
angles is more consistent (middle panels in Figures 6a and 6b). The total mean and RMS errors of the temperature and specific humidity analysis before and after assimilating the 52 GPS/MET occultation profiles above 850 hPa are presented in Table 1.

It is found that the degradation in the moisture analysis after the bending angle assimilation occurs mostly when the observed bending angle has a negative mean bias compared with the background (Figure 6c, OBS - BKG <0). This may be associated with the N negative bias problem of the GPS/MET observations [Rocken et al., 1997]. For example, the observed GPS-15, GPS-40, GPS-44, and GPS-49, for which the degradation was significant (Figure 5), had large negative bias compared with the background (Figure 6c).

4.3. Analysis Fit to Observations During the 11-Day Cycle

Having tested the GPS/MET bending angle assimilation method against the independent radiosonde observations collocated with GPS/MET occultations, we proceed to the two experiments (NOGPS and BOTH) which carry out 11-day cycles of data assimilation. As an indication of the quality of the analysis, the fit of the analysis, background, and forecasts from NOGPS and BOTH to GPS/MET observations and conventional observations will be examined and compared in the following.

Figure 7 shows the fit of the GPS/MET bending angles to the background fields and the analyses produced from the NOGPS and BOTH experiments. Compared with the background fields, the fit to GPS/MET is not much improved through the assimilation of conventional data only (Figure 7a). A slight degradation is found in the NOGPS analysis in the lower troposphere. As mentioned in section 2, out of 837 GPS/MET occultations, there are only 52 for which radiosonde observations are available within a 200-km distance. Therefore there is very little overlap in the distribution of observation locations between the GPS/MET and conventional data. The degradation of the NOGPS analysis in the lower troposphere may indicate that the background error correlations are probably not sufficient to resolve the vertical scales that are represented in the GPS/MET measurements. However, assimilating the GPS/MET observations greatly improves the fit to the GPS/MET data (Figure 7b), which confirms that the data assimilation is working effectively.

The fit of temperature and moisture to the conventional observations for the analyses produced from the NOGPS and
BOTH assimilations is presented in Figure 8. The temperature analysis in BOTH is colder than that in NOGPS at all vertical levels. The temperature in BOTH fits the radiosonde observations better than NOGPS between 200 and 800 hPa. Below and above this layer, the temperature analysis is degraded, especially above 200 hPa. The large errors found in the temperature analysis above 200 hPa are probably caused by the observation error variances, which are too large, and estimated on the basis of the background and observation differences. On average, changes in the specific humidity fields due to the addition of GPS/MET occultations to the conventional data are negligible.

4.4. Verification of 6-hour Forecasts With Radiosonde Observations

The quality of the analyses with and without GPS/MET bending angles can be examined further by comparing the 6-hour forecasts with all the conventional observations (Figure 9) and only the 56 collocated radiosondes (Figure 10). The 6-hour forecasts of temperature in BOTH is also colder than those of NOGPS. The 6-hour forecasts from the BOTH analysis is more moist than those of NOGPS. Verified by the conventional observations, the 6-hour forecasts of both temperature and specific humidity are slightly improved between 200 and 850 hPa. Degradation of the temperature analysis below 850 hPa and above 200 hPa, seen in Figure 8, is also shown in the 6-hour forecasts. Very small improvement above 850 hPa and small degradation below this level is found in the moisture forecasts. The verification of the moisture forecasts produced with and without GPS/MET bending angles is difficult due to the large temporal and spatial variability of water vapor.

We examined the vertical distributions of the observed and modeled bending angle, temperature, and specific humidity. The soundings for which the bending angle data assimilation produced a closer fit of the background (the 6-hour forecast) to radiosonde observations are found to be mostly located in
middle latitudes. Figure 11 presents simulated (from background field) and observed vertical profiles of bending angle, temperature, and specific humidity (bending angle from GPS/MET and temperature and specific humidity from radiosonde) of one such sounding. The radiosonde data show a relatively smooth vertical variation and comparatively small values of specific humidity (Figure 11c). Degradation of the background (6-hour forecasting) specific humidity, using radiosonde as the truth, occurred mostly in the tropics. Figure 12 gives one such example. The GPS/MET occultation was located at (144°W, 28°S) at 0000 UTC, June 28, 1995, and the radiosonde was at (145°W, 29°S) 2312 UTC, June 28, 1995. The distance between the GPS/MET occultation and the radiosonde sounding is about 178 km. The radiosonde data indicate a strong low-level inversion and large values of specific humidity.

Table 2. Mean Differences Between 6-Hour Forecasts and All Conventional Observations Above 850 hPa

<table>
<thead>
<tr>
<th></th>
<th>Temperature, °C</th>
<th>Specific Humidity, g kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Southern Hemisphere, 90°S–30°S</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOGPS</td>
<td>0.4</td>
<td>0.12</td>
</tr>
<tr>
<td>BOTH</td>
<td>0.1</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>Tropics, 30°S–30°N</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOGPS</td>
<td>0.1</td>
<td>0.09</td>
</tr>
<tr>
<td>BOTH</td>
<td>0.0</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Northern Hemisphere, 90°N–30°N</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOGPS</td>
<td>0.1</td>
<td>0.07</td>
</tr>
<tr>
<td>BOTH</td>
<td>0.0</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Figure 14. Same as Figure 13 except for the 44th radiosonde sounding.
lower troposphere, and a quality control procedure for the GPS/MET observations.

Table 2 presents the mean errors of the 6-hour forecasts from NOGPS and BOTH compared to conventional observations in the Northern Hemisphere, the tropics, and the Southern Hemisphere. The improvement in the 6-hour forecasts is greater in the Southern Hemisphere and the tropics than in the Northern Hemisphere. This is probably due to the larger forecast errors in the Southern Hemisphere and the tropics than in the Northern Hemisphere.

Although there are more than 837 GPS/MET radio occultation soundings assimilated into the analyses, we note that these soundings are distributed over an 11-day period. They are still far fewer than conventional observations. Also, satellite cloud-cleared radiances [Derber and Wu, 1998] were not included in our experiments. A comparison of the 6-hour forecasts with and without GPS/MET observations against conventional observations, although statistically more significant than those presented by Zou et al. [2000], is still inadequate to give a complete picture of the impact of GPS/MET data on NWP or the impact of a large number of GPS data on NWP. Improvement over data-void regions are also not reflected in these calculations.

4.5. Verification of 5-Day Forecasts With Conventional Observations

A final measure of the impact of the assimilation of GPS/MET data can be evaluated by comparing forecasts from each analysis. Two sets of 5-day forecasts were produced twice a day during the 11-day period for NOGPS and BOTH for a total of 20, 18, 16, 14, and 12 forecasts for the 1-day, 2-day, 3-day, 4-day, and 5-day forecast periods, respectively. The forecast of both sets were verified against the NOGPS analysis. The averaged 500-hPa temperature RMS errors are shown in Figure 15a for the Northern Hemisphere and in Figure 15b for the Southern Hemisphere. The Northern Hemisphere results are only slightly improved by assimilating the GPS/MET bending angle observations. In the Southern Hemisphere the improvement is noticeably larger. It is interesting and encouraging to note that the improvement persists during the entire 5-day forecast.

5. Conclusions

The impact of assimilating GPS/MET radio occultation bending angles on global numerical weather forecasts is evaluated. The results from this study using 837 observed profiles of bending angles over an 11-day period from the single satellite, proof-of-concept GPS/MET mission are encouraging. We found a small but positive impact on numerical forecasts from the inclusion of the GPS/MET bending angles in the NCEP analyses assimilating only the conventional observations (e.g., satellite cloud-clear radiances are not included), even with the small number of occultations compared to conventional data. A better assessment of the impact of GPS occultation data on weather forecasts requires an inclusion of all concurrent data.
types, and a larger GPS data set, such as that proposed in the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) experiment [Rocken et al., 2000]. COSMIC promises to deliver ~3000 soundings per day. These soundings are expected to be of higher quality than the GPS/MET soundings and over 90% of them are expected to penetrate to within 1 km of the surface. Before this happens, further research is needed to best quantify the observation error covariances and the background error covariances, as well as to develop a fast bending angle observation operator with reasonable accuracy. Also, a quality control method, which removes low-quality GPS observations, needs to be developed.

The simple relation between the refractivity and the temperature and humidity may render the GPS-derived refractivity to be the quantity chosen for an operational application where computational cost becomes a major concern. Assimilation of GPS refractivity [Zou et al., 1995, 2000] eliminates errors introduced by the ambiguity between temperature and humidity. However, a direct link between the local atmospheric refractivity and the GPS refractivity may not be the most accurate way to incorporate the GPS/MET measurements into a numerical model. The GPS-derived refractivity is not the local value, but a complicated function of the refractivity along the ray. Thus proper assimilation of the refractivity data should affect the model fields not only at the tangent point of the ray but also along the rays. An effective and accurate GPS refractivity assimilation must take care of the nonlocal nature of the GPS refractivity retrieval. The assimilation of bending angles described in this paper may serve as a benchmark for the development of such a method that assimilates the GPS-derived refractivity through a functional relationship to local refractivities along the ray path.

Acknowledgments. We thank S. Mango from the National Polar-Orbiting Operational Environmental Satellite System Integrated Program Office, Pamela Stephens and Jay S. Fein from National Science Foundation, and S. Lord, J. Derber, and J. G. Sela from NCEP, whose support made it possible to complete this work. This research is supported by the National Polar-Orbiting Operational Environmental Satellite System Integrated Program Office under SMC/CIPN project order Q000C1737600086, and the National Science Foundation under project ATM-9812729.

References


Hui Liu, H. Shao, and X. Zou, Department of Meteorology, Florida State University, Tallahassee, FL 32306, USA. (zou@met.fsu.edu)

R. A. Anthes, University Corporation for Atmospheric Research, Boulder, CO, USA.

J. C. Chang and J.-H. Tseng, Central Weather Bureau, Taipei, Taiwan.

B. Wang, LASG, Institute of Atmospheric Physics, CAS, Beijing, China.

(Received January 9, 2001; revised August 9, 2001; accepted August 10, 2001.)