Comparison of Local and Nonlocal Observation Operators for the Assimilation of GPS RO Data with the NCEP GSI System: An OSSE Study

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ABSTRACT

In this study, an Observing System Simulation Experiment (OSSE) is performed to evaluate the performance of a nonlocal excess phase operator and a local refractivity operator for a GPS radio occultation (RO) sounding that passes through the eye of Hurricane Katrina as simulated by a high-resolution model, with significant horizontal refractivity gradients. Both observation operators are tested on the NCEP gridpoint statistical interpolation (GSI) data assimilation system at 12- and 36-km horizontal resolution. It is shown that the shape and magnitude of the analysis increments for sea level pressure, temperature, and water vapor mixing ratio exhibit significant differences between the use of local and nonlocal operators. The nonlocal operator produces more accurate analyses when verified against the “truth” derived from the ground truth run. It is found that the improvements of the analysis with the use of the nonlocal operator over that of the local operator are essentially the same at 12- and 36-km horizontal resolution. An additional experiment is performed over a region with small horizontal gradients. As expected, the use of both nonlocal and local operators produces similar results over such a region.

1. Introduction

The global positioning system (GPS) radio occultation (RO) limb sounding technique has emerged as a robust global observing system (Ware et al. 1996). The GPS RO technique can provide all-weather, high-vertical-resolution observations that require no calibration (Kursinski et al. 1997). The GPS/Meteorology (MET) and the Challenging Mini-Satellite Payload for Geoscientific Research and
Applications program (CHAMP) missions have demonstrated that GPS RO measurements have accuracy compatible with or better than that of radiosondes (Kursinski et al. 1996; Rocken et al. 1997; Zou et al. 2000; Wickert et al. 2001; Poli and Joiner 2003; Kuo et al. 2004; Healy and Thepaut 2006). In April 2006, the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission (Anthes et al. 2000; Rocken et al. 2000; Anthes et al. 2008) was successfully launched from the Vandenberg Air Force Base; this marked the beginning of a new era of GPS RO science. Since launch, COSMIC has been providing approximately 1500–2500 globally distributed soundings per day in near–real-time. The COSMIC GPS RO soundings are currently being used at several global operational NWP centers, including the National Centers for Environmental Prediction (NCEP; Cucurull and Derber 2008), the European Centre for Medium-Range Weather Forecasts (ECMWF; Healy 2008), the Met Office (UKMO), and Météo France (Poli et al. 2009).

The raw GPS RO measurements are the phase and amplitude of the GPS radio wave. From these measurements, vertical profiles of bending angles and refractivity can be derived. As discussed in Kuo et al. (2000), GPS RO data in various forms, ranging from excess phase, bending angle and refractivity to retrieved temperature and moisture can be used for assimilation. Based on many previous studies (Eyre 1994; Zou et al. 1999; Kuo et al. 2000; Syndergaard et al. 2005), GPS RO bending angle and refractivity are the two popular choices for the assimilation of GPS RO observations. The assimilation of bending angle profiles using a ray-tracing model (Liu and Zou 2003; Shao and Zou 2002; Poli and Joiner 2004; Healy et al. 2007) has the advantage that the effects of horizontal refractivity gradients are accounted for. However, the accurate calculation of ray paths that depend on refractivity through an NWP model is computationally expensive. That is why the local refractivity operator is often used to assimilate the GPS RO data. With this approach, the Abel-retrieved (AR) refractivity is assimilated into the model as local refractivity, which is related to pressure, temperature, and humidity at the estimated ray tangent points (TPs). Recently, Healy (2007) has assimilated GPS RO data using the local bending angle approach, which is essentially equivalent to the assimilation of local refractivity. However, treating the AR refractivity as local refractivity may result in significant representativeness errors in the presence of strong horizontal gradients of temperature or water vapor, especially for high-resolution NWP models (Sokolovskiy et al. 2005a).

To address these issues, Syndergaard et al. (2005) developed a “nonlocal refractivity operator,” which is sufficiently accurate and computationally efficient. The nonlocal refractivity operator is motivated by the suggestion that GPS RO refractivity profiles derived with the Abel transform should be interpreted as “mesoscale-sized along-track averages” (Melbourne et al. 1994). It is composed of two steps: (i) a profile of phase delays is calculated assuming a straight-line path in the occultation plane; and (ii) these delays are then inverted with an Abel transform. Later, Sokolovskiy et al. (2005a) proposed an alternative “nonlocal excess phase operator,” which assimilates the straight-line phase delay directly. Theoretically both the nonlocal refractivity and excess phase operators are equivalent, but the excess phase operator allows more optimal discrete representation for integration of refractivity along the ray path that allows minimization of the errors arising from the discretization. Although neither method is expected to be more accurate than the assimilation of bending angles with a 2D ray-tracing operator, both of them are computationally efficient and, to a large degree, capable of taking into account the effect of horizontal gradients. Another advantage of both nonlocal operators is that they are applied below the top of an atmospheric model and thus do not require extrapolation of the model atmosphere above the model top. Even though the 2D bending angle operator has been implemented in ECMWF data assimilation system (Healy et al. 2007), testing more simple and computationally efficient approaches that provide sufficient accuracy in accounting for horizontal gradients for the use in other NWP systems remains highly desirable.

Recently, Liu et al. (2008) implemented the nonlocal excess phase operator developed by Sokolovskiy et al. (2005a) into a (Weather Research and Forecasting) WRF-based ensemble adjustment Kalman filter (EAKF) data assimilation system, and compared its performance with the local refractivity operator for the month of January 2003 over North America. They assimilated a total of 536 GPS RO profiles from CHAMP using both operators with a 50-km WRF/EAKF system. The resulting analyses are evaluated against nearby radiosonde observations that were not used in the assimilation. They showed that the bias and RMS errors of the analyses of water vapor and temperature using the nonlocal excess phase operator were significantly reduced compared with those using the local operator in the troposphere when the only additional observations are satellite cloud drift winds. The improved performance of the nonlocal operator was reduced when radiosonde observations were also assimilated together with satellite cloud drift winds.

While the results of Liu et al. (2008) using the WRF/EAKF system are very encouraging, it is desirable to perform additional studies. First, it is important to
implement the nonlocal observation operator in an operational data assimilation system, and to assess its performance. Such study is an important first step before such an operator is used for operational assimilation of GPS RO data. Second, it is often challenging to clearly assess the impact of an observation operator in a real-data study, as the system is very complex, and many other factors can influence the results. Third, it is desirable to examine the impact of observation operator for a severe weather system, such as a hurricane, where there are significant horizontal inhomogeneities.

In this paper, we perform an Observing System Simulation Experiment (OSSE) with the NCEP operational gridpoint statistical interpolation (GSI) data assimilation system (Wu et al. 2002) to assess the performance of the nonlocal excess phase operator developed by Sokolovskiy et al. (2005a). The implementation and impact assessment of GPS RO nonlocal excess phase operator in the NCEP GSI system in an OSSE framework is an important step before real-data studies and operational applications.

This paper is structured as follows: section 2 briefly reviews the NCEP GSI data assimilation system and the GPS RO local refractivity and nonlocal excess phase operators. The experiment setup is presented in section 3 and the results of comparison experiments are analyzed in section 4. A summary is given in section 5.

2. Description of the GSI system and GPS observation operators

The three-dimensional variational data assimilation (3DVAR) GSI data assimilation system has been developed as the next-generation operational global analysis system to replace the NCEP global spectral statistical interpolation (SSI) analysis system (Derber et al. 1991). The GSI can also be used with mesoscale NWP systems [e.g., the WRF nonhydrostatic mesoscale model (NMM) and the Advanced WRF model (ARW)]. The GSI uses recursive filters in gridpoint space to model the action of the background error covariance matrix upon the spatial distribution of observation increments (Wu et al. 2002). A more detailed explanation of the GSI system can be found on the NCEP GSI Web site (http://www.emc.ncep.noaa.gov/gmb/treadon/gsi).

Currently, the GSI has the ability to assimilating the GPS RO data only with the local refractivity operator (Cucurull et al. 2007). It is a simple and low-computational-cost approach to calculate the atmospheric refractivity with

$$N = 77.6\left(\frac{p}{T}\right) + 3.73 \times 10^5\left(\frac{p_v}{T^2}\right),$$

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).

Since the calculated local refractivity at the ray tangent point is a point value and Abel-inverted GPS RO refractivity is a weighted average of the atmospheric refractivity along the ray path and above (Ahmad and Tyler 1998), significant errors could arise over regions with strong horizontal gradients of refractivity if the local refractivity operator is used to assimilate the AR GPS RO refractivity. To reduce these representativeness errors, Sokolovskiy et al. (2005a,b) developed the nonlocal excess phase operator to account for the effect of the horizontal gradients.

Here we briefly summarize the nonlocal excess phase operator introduced by Sokolovskiy et al. (2005a). As the observational variable in this operator, the excess phase is not a direct product (such as bending angle or refractivity) derived from GPS original measurements, but a virtual value obtained by integrating the refractivity along some fixed virtual ray path that does not depend on refractivity but is close to the true ray path. The latter means linearity of the excess phase on refractivity (though it remains non-linear on the model variables) and significantly simplifies the calculations. The virtual observable, excess phase $S_{\text{obs}}$ and its model counterpart $S_{\text{mod}}$ are given by the following equations:

$$S_{\text{obs}} = \int_{\text{ray}} N_{\text{RO}}(r) \, dl \quad \text{and} \quad S_{\text{mod}} = \int_{\text{ray}} N_{\text{mod}}(r) \, dl,$$

where $r$ is the radius vector from $r = r_e + z$, $r_e$ is the local center of curvature of the mean sea level surface, and $dl$ is the differential ray pathlength, $z$. This produces a new observable, excess phase $S_{\text{obs}}$ and a corresponding model counterpart $S_{\text{mod}}$. Some properties of the nonlocal excess phase operator (as being applied here) should be noted: (i) the assimilation is performed at the levels of the observations, (ii) both observation and model refractivities are integrated using the same finite-difference representation (to minimize the representativeness error), (iii) the integration is confined below the top of the model, (iv) the rays penetrating below terrain are not considered, (v) the AR refractivity is treated as spherically symmetric, (vi) the coordinates (latitude and longitude) of the ray perigee vary with height, and (vii) the ray paths are represented by straight lines tangent to GPS low-Earth-orbiting (LEO) rays at their estimated perigee points.

3. Experiment design

OSSEs are useful in assessing the potential impact of different approaches for the assimilation of GPS RO
observations. Kuo et al. (1997) used the OSSE approach to assess the potential impact of GPS RO data on a developing midlatitude cyclone. In an OSSE, a high-resolution model [representing a physically realistic atmosphere, which is often called the “nature” run (Atlas 1997)] is used to simulate observations from a hypothetical observing system. These observations are assimilated into a lower-resolution model (representing a typical operational data assimilation/forecast system). The effectiveness of the assimilation can be assessed by comparing the results with the known “truth” (nature run). In this study, the ARW-WRF model (Skamarock et al. 2005) was used for the nature run, and we focus on the case of Hurricane Katrina (2005).

The nature run (Fig. 1) is a 72-h forecast with the ARW model initialized at 0000 UTC 27 August 2005 with the GFS global analysis. The ARW model is configured with a 4-km grid spacing, 361 × 361 mesh size, and 38 layers between surface and 50 mb (~20 km); and a combination of sophisticated physics packages [e.g., Thompson graupel microphysics, Kain–Fritsch (new Eta) cumulus parameterization, Dudhia shortwave and Rapid Radiative Transfer Model (RRTM) longwave radiation, and Yonsei University (YSU) PBL]. To assess the realism of the nature run, we show in Figs. 1a,b the track and intensity of the nature run and observation. At 0000 UTC 28 (i.e., the 24-h forecast of the nature run), the errors of track and central sea level pressure (CSLP) are 40 km and 9 mb according to Figs. 1c and 1d, respectively. This is the time that the outputs of the nature run are used to simulate the observation, as well as the assimilation experiments are conducted using the NCEP GSI. Figure 1 shows that the nature run successfully simulates the development and movement of Hurricane Katrina as verified against the observations. The realism of the nature run provides a solid basis for the OSSEs.

To evaluate the performance of local and nonlocal observation operators in the presence of significant horizontal gradients, the model data from the nature run are extracted along a north–south cross section cutting through the center of the hurricane at 24-h forecast time (0000 UTC 28 August 2005). The first step is to simulate the AR GPS RO refractivity soundings from the nature run along this cross section. Figure 2 shows temperature,
moisture (Fig. 2a), and refractivity (Fig. 2b) along the cross section that cuts through the eye of Hurricane Katrina in the nature run. Next we simulate two GPS RO soundings in this vertical plane. For this purpose we extract the 2D refractivity field in the occultation plane at 4-km horizontal resolution, by interpolating from ARW 3D grid fields, and extend it exponentially above the top of the grid. We assume GPS (immovable) and LEO (in circular orbit). Then, we simulate observables by numerically solving ray equations (by the fourth-order Runge–Kutta method). The ray arrival angle at LEO is used for calculation of the impact parameter. For calculation of the ray takeoff angle at GPS and of the bending angle we use the assumption of spherical symmetry (Snell’s law). Thus, we are mimicking real observations (we note that the calculated bending angle and impact parameter, in the presence of horizontal gradients, are not equal to the true bending angle and the impact parameter at the tangent point). In this OSSE we neglect the effect of cross-track horizontal gradients that introduce smaller errors than those arising from representation of AR refractivity as local. Thus, calculated bending angles as functions of the impact parameters are subject to Abel inversion for calculation of refractivities as functions of heights over the sea surface (after subtraction of the earth curvature radius). More details on the ray tracing through the grid refractivity field and on the Abel inversion can be found in Sokolovskiy et al. (2005a). The vertical curves in Fig. 2b show the ray TP trajectories for the two simulated GPS RO soundings. One sounding (RO1) is located (at about 25°N) within the eye of Hurricane Katrina, and the other (RO2) is located (between 21° and 22°N) outside the eye.

Effective assimilation of a particular type of observation requires proper specification of observational errors. For the nonlocal excess phase operator, mapping of the refractivity errors into the excess phase space needs the knowledge of vertical refractivity error scales, vertical and horizontal scales of the refractivity structures, and thus requires the use of either model or observational
data. In this study, we adopt the observational errors estimated by Chen et al. (2009), which were obtained based on the 1-month statistics of WRF ARW over the western Pacific and the CHAMP data with the method of Hollingsworth and Lönnberg. For the GPS RO local refractivity operator, we still use the observational errors estimated by Chen et al. (2009), which are calculated following the same procedures using the same datasets as those of the nonlocal observation operator. Additional discussions on the observation errors are presented in the appendix. We note that the observational errors of the excess phase are smaller than the errors of the AR refractivity not only in fraction of their mean values, but also in fraction of their standard deviations of the means, as found by Sokolovskiy et al. (2005b). This indicates that assimilation of the excess

![Figure 4](image-url)
phase allows for the extraction of more information about horizontal atmospheric structures than of the AR refractivity.

To evaluate the performance of local and nonlocal operators on the analysis fields in the GSI system, we performed the same set of experiments on both the high (12 km) and low (36 km) horizontal resolutions domains. For the high-resolution experiments, the simulated GPS RO soundings are assimilated into the 12-km GSI data assimilation system. The background field for GPS RO data assimilation is obtained from the NCEP analysis at 0000 UTC 28 August 2005. A large number of parallel experiments were performed for both the local and nonlocal operators to investigate various strategies for GPS RO data assimilation. Similarly, these experiments were repeated in the lower-resolutions (36 km) domain to evaluate the impact of model resolution on GPS RO data assimilation.

4. Comparison of the assimilation results obtained with local and nonlocal observation operators

We address the following question: how do the local and nonlocal GPS RO observational operators affect the analysis, and to what extent would the improvement to analysis be achieved by the assimilation of GPS RO data with the NCEP GSI data assimilation system. Here, for brevity, we denote the results of the control (no data assimilation) experiment, initialized from the NCEP analysis on 0000 UTC 28 August 2005, as the “CTRL.” The results of the assimilation experiment obtained with the local refractivity operator are denoted as “LOC,” and those obtained with the nonlocal excess phase operator as the “NON-LOC.” We will compare these results in terms of innovation, horizontal and vertical increments, and verify them against the truth (which is obtained from the nature run). In these assimilation experiments, all other observations are excluded except the one single simulated COSMIC GPS RO refractivity profile. This allows us to clearly isolate and assess the impact and performance of the local and nonlocal observation operators.

At first, we compare LOC and NON-LOC with assimilation of only the RO1 GPS sounding in Fig. 2b for the 12-km GSI data assimilation system. For different observation variable ($O$) in local refractivity and nonlocal excess phase operators, the fractional difference ($O_{obs} - O_{mod})/O_{obs}$ is used to compare the performance
of the two operators. Here $O_{\text{obs}}$ and $O_{\text{mod}}$ stand for observed [refractivity ($N$) for LOC, excess phase ($S$) for NON-LOC] and modeled values, respectively. In data assimilation, the statistics of the observation minus background ($O - B$) and observation minus analysis ($O - A$) departure (where $B$ and $A$ are background and analysis projected in the space of observation) distributions are useful diagnosis. Figure 3 presents a comparison of fractional differences of $O - B$ and $O - A$ for LOC and NON-LOC. The fact that $O - A$ is smaller than $O - B$ for both operators indicates that GPS RO refractivity observations have been assimilated successfully by the GSI system with both operators. The curves have similar structures for the LOC and NON-LOC, but the fractional difference for the NON-LOC is up to 2 times smaller than for the LOC below 6 km, regardless of $O - B$ or $O - A$.

Figure 4 shows the horizontal increments of sea level pressure ($P$), temperature ($T$), and water vapor mixing ratio ($q$), respectively. The left panels show the horizontal increments for LOC and the right ones for the NON-LOC. These figures show that the increments of the NON-LOC are broadened significantly and stretched into an elliptical shape along the ray path (from south to north). This is to be expected because the GPS RO observation is not a point measurement, but rather, a weighted average of the atmospheric refractivity along the ray path and above. Another important point is that the NON-LOC can produce a stronger impact on the initial field than LOC. For example, the $q$ increment at 850 hPa is $-1.65$ g kg$^{-1}$ for LOC and $-1.89$ g kg$^{-1}$ for NON-LOC.

Figure 5 shows the north–south vertical cross sections of increments of $T$ and $q$ at the center of Hurricane Katrina. It shows again that the shape and magnitude of the increments in NON-LOC can differ significantly from those of LOC in the presence of strong horizontal gradients. As will be shown later in Fig. 6, the temperature of the first-guess field is colder than that of the nature run. The LOC has only a slight impact on the temperature between 4 and 6 km, while the NON-LOC removes this cold error more substantially.

In this set of experiments, data assimilation is performed on the 12-km GSI system, while the resolution of the nature run is 4 km. To evaluate the performance of GPS RO refractivity assimilation experiments, we interpolate the nature run (by averaging and downsampling) to the 12-km grid. Figure 6 shows the differences in $T$ and $q$ between the assimilation experiments and the nature run. In comparison with CTRL, the differences from both NON-LOC and LOC become smaller in the vicinity of the hurricane’s center after the assimilation of the simulated GPS RO observations. Furthermore, the temperature of NON-LOC is obviously closer to the nature run than LOC at higher levels. For the water vapor mixing ratio, the NON-LOC is closer to the nature run than the LOC at lower levels.

To further evaluate the performance of these two observation operators, we calculate the mean and standard deviation errors of the differences between the results of
the assimilation experiments and the nature run within the 250 km × 250 km domain centered at the eye of the hurricane. Figure 7 shows that the mean errors from the NON-LOC are substantially smaller than those from the CTRL and LOC experiments in the two atmospheric layers (~1–3 km and above 6 km) for $T$, almost the entire atmosphere from surface to 10 km for $q$. The standard deviation of the temperature indicates better performance of NON-LOC over LOC in the upper troposphere, while that of the moisture indicates noticeably better performance of NON-LOC in the lower troposphere.

To further quantify the results of assimilation with LOC and NON-LOC in comparison with CTRL (no assimilation) we define the improvement factor $\alpha = 1 - |\Delta_{\text{ass}}|/|\Delta_{\text{ctrl}}|$, where $\Delta$ is either mean or standard deviation of either $T$ or $Q$ from the nature run, averaged on the model vertical levels, for either LOC (assimilation) or NON-LOC (assimilation) and the CTRL (ctrl). If errors of the assimilation experiments are as large as CTRL, then $\alpha$ will be zero, and there is no improvement. The results are shown in Table 1, separately for 12- (rows 1, 2) and 36-km (rows 3, 4) horizontal resolutions. These results again support the generally superior performance of the NON-LOC over LOC. In general, the improvement for NON-LOC is more than 2 times greater than that for LOC. Thus, the use of the nonlocal operator with

![Figure 7](image_url)
the integration of refractivity along the ray path results in better performance of the GSI system than the use of the local operator. The results with 12- and 36-km horizontal resolutions show similar improvements in the NON-LOC compared to the LOC in terms of mean and standard deviation errors. However, further degradation of the horizontal resolution (with grid size greater than 100 km) is likely to result in the reduction of the differences in performance between LOC and NON-LOC as discussed in Sokolovskiy et al. (2005a).

It is also useful to compare the performances of LOC and NON-LOC for a GPS RO sounding located over a region with small horizontal gradients (which is somewhat similar to representation of the truth by a low-resolution model). For this purpose, we simulate another GPS RO sounding (RO2 in Fig. 2b) about 400 km to the south of the center of the storm, and repeat both the LOC and NON-LOC data assimilation experiments for this sounding. Figure 8 shows the north–south vertical cross sections of analysis increments of $T$ and $q$ with GPS RO sounding RO2 located at the center. It shows that the shape and magnitude of the analysis increments (in either temperature or water vapor) are very similar between LOC and NON-LOC. Table 2 shows the improvement factor $\alpha$ of LOC and NON-LOC over CTRL for both 12- and 36-km horizontal resolutions. The results show smaller difference between the local and nonlocal operators over regions with small horizontal gradients; however, the nonlocal operator still gives better results in general.

5. Discussion and conclusions

In this study, the GPS RO nonlocal excess phase operator has been implemented and tested successfully in the NCEP GSI data assimilation system. Using the nonlocal excess phase operator, the information about the along-track horizontal structure of refractivity can be included while the operator remains simple and computationally inexpensive. The comparisons of local

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<th>$T_{\text{mean}}$</th>
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<td>34.5</td>
<td>1.8</td>
<td>72.1</td>
<td>4.9</td>
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Table 1. The improvement coefficients $\alpha$ (% defined in the text) for LOC and NON-LOC experiments at 12- and 36-km resolution with assimilating GPS RO1 in Fig. 2b at 0000 UTC 28 Aug 2005.
and nonlocal operators in the OSSE framework clearly illustrate that the nonlocal excess phase operator gives a superior performance on the analysis fields in the presence of strong horizontal gradients in the vicinity of a hurricane. As a 2D operator, the nonlocal operator produces analysis increments with shape and magnitudes significantly different from those of the local refractivity operator. We also found that the improvements associated with the nonlocal operator are essentially the same at 12- and 36-km resolutions. This suggests that at these mesoscale resolutions, the use of a nonlocal observation operator is desirable. For a GPS RO sounding located over a region with small horizontal gradients, there is less difference in performance between these two operators, which is to be expected based on the results of Sokolovskiy et al. (2005a); however, the nonlocal operator still gives slightly better results. In the future, we will investigate the performance of these two operators for other types of atmospheric systems (e.g., atmospheric fronts or atmospheric rivers) with real data assimilation.

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APPENDIX

Observation Errors and Sensitivity Tests

The observation errors specification is an importance component of a data assimilation system. The analysis results are directly influenced by the observation errors.

For this paper, we use the observation errors produced by Chen et al. (2009). Chen et al. (2009) calculated the observation errors using the CHAMP GPS RO data during the period of 15 August–15 September 2003 with a 45-km WRF model over the western North Pacific. The calculation of the forecast errors followed the method of Hollingsworth and Lönnberg (1986). A total of 314 CHAMP soundings were used in the study. The calculation of observation errors for both the local refractivity observation operator and the nonlocal excess phase operator followed the same procedures, and used the exact same datasets. Figure A1 shows the observation errors from Chen et al. (2009). Also shown is the default GPS RO observation errors used in GSI for local refractivity observation operator. For the Chen et al. (2009) study, the nonlocal observation error is about half of that of local observation error. As explained by Sokolovskiy et al. (2005a), this is related to the fact that use of the nonlocal operator significantly reduces the representativeness errors. The local observation errors from Chen et al. (2009) are compatible with those produced by Kuo et al. (2004). We found that the observation errors used in the GSI differ significantly from

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<td>10.2</td>
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Fig. A1. Observation errors provided by Chen et al. (2009): thick dashed curve, for local observation error, and thin dashed curve, for nonlocal observation error. The local observation error used in standard GSI data simulations is the solid line.
those of Chen et al. (2009). Between 2 and 10 km, the GSI observation errors are smaller than the Chen et al. (2009) estimates, varying from 0.5% to 1%.

To assess the sensitivity of data assimilation results to the specification of observation errors, we performed a data assimilation experiment using the local operator with the observation errors from Chen et al. (2009) and the GSI observation errors, and compared the results with those obtained with the use of the nonlocal observation operator and the observation errors from Chen et al. (2009). These results are presented in Fig. A2. The top and bottom panels show temperature and moisture increments, respectively. The left and middle panels correspond to the use of local operator with observation errors from GSI (left panels) and with the Chen et al. (2009) observation errors (middle panels), and the right panels are for the nonlocal observation operator using the Chen et al. (2009) observation errors. We found no significant differences between the results of two experiments with local observation operators using different observation errors. They are both significantly different from the results using the nonlocal observation operator. This suggests that the GSI data assimilation system is not very sensitive to specification of the observation errors. Clearly, the use of different observation operator has a much larger impact.

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