Improved Analyses and Forecasts of Hurricane Ernesto’s Genesis Using Radio Occultation Data in an Ensemble Filter Assimilation System

HUI LIU, JEFFREY ANDERSON, AND YING-HWA KUO
National Center for Atmospheric Research, Boulder, Colorado

(Manuscript received 2 February 2011, in final form 23 May 2011)

ABSTRACT

Radio occultation (RO) refractivity observations provide information about tropospheric water vapor and temperature in all weather conditions. The impact of using RO refractivity observations on analyses and forecasts of Hurricane Ernesto’s genesis (2006) using an ensemble Kaman filter data assimilation system is investigated. Assimilating RO refractivity profiles in the vicinity of the storm locally moistens the analysis of the lower troposphere and also adjusts the wind analysis in both the lower and upper troposphere through forecast multivariate correlations of RO refractivity and wind. The model forecasts propagate and enhance the added water vapor and the wind adjustments leading to more accurate analyses of the later stages of the genesis of the storm. The root-mean-square errors of water vapor and wind forecasts compared to dropsonde and radiosonde observations are reduced consistently. As a result, assimilating RO refractivity data in addition to traditional observations leads to a stronger initial vortex of the storm and improved forecasts of the storm’s intensification. The benefits of the RO data are much reduced when the RO data in the lower troposphere (below 6 km) are ignored.

1. Introduction

In general, six factors are necessary for tropical cyclones to form and develop (Gray 1968). These factors are: warm water temperatures of at least 26.5°C down to a depth of at least 50 m; rapid cooling with height in the atmosphere, which allows the release of the heat of condensation that powers a tropical cyclone; high humidity, especially in the lower-to-mid troposphere; small vertical wind shear; a distance greater than five degrees of latitude away from the equator; and a preexisting system of disturbed weather.

Accurately estimating two of the six necessary factors, the rapid cooling with height and the high humidity in the lower-to-middle troposphere, requires good measurements of temperature and water vapor in the troposphere. The global positioning system (GPS) radio occultation (RO) technique can provide high-vertical-resolution atmospheric refractivity observations that are a function of water vapor and temperature in the troposphere in all weather conditions. The RO refractivity observations have a vertical resolution as small as a few hundred meters and a horizontal footprint on the order of 250 km in the lower troposphere (Kursinski et al. 1997). Therefore, RO refractivity observations can provide valuable information about water vapor and temperature in the environment of tropical storms, which is crucial for forecasting their subsequent evolution.

It has been difficult to demonstrate benefits from assimilating RO observations on analyses and forecasts of tropical storms, especially averaged over a number of cases. However, positive impacts of RO data have been shown for global forecasts (e.g., Healy and Thépaut 2006; Healy 2008a,b; Liu et al. 2001; Zou et al. 2004; Cucurull and Derber 2008). One challenge is that the environment of tropical storms is often moist convective and latent heat release is the driving factor for tropical storms’ development. Forecast errors may be strongly flow dependent and forecast errors of wind and temperature may be strongly correlated with water vapor. It is advantageous to have a good multivariate, flow-dependent estimate of the forecast error covariance to correct forecast errors in water vapor, temperature, and wind in a consistent way. This reduces imbalance in the analyses and also generates more accurate wind analyses. These result in better forecasts of the development...
of tropical storms by more accurately representing the vertical wind shear.

Ensemble data assimilation techniques provide one way to address this challenging problem by estimating the forecast error covariance using short-range ensemble forecasts. The estimated covariance is fully multivariate and varies with the synoptic situation. A few preliminary studies with assimilation of RO refractivity in ensemble assimilation systems have demonstrated benefits for forecasts of Hurricane Ernesto (2006) and Typhoon Shanshan (2006; Liu et al. 2007; Anthes et al. 2008; Kuo et al. 2009; Anderson et al. 2009). In this study, we examine the details of how RO refractivity observations impact the analyses and forecasts of a tropical storm using an ensemble data assimilation system. In particular, the impacts of RO data on analyses and forecasts of water vapor, temperature, and wind in the convective environment of a tropical storm are examined. Assimilation of several key RO refractivity observations upstream of the developing tropical storm reduces errors in water vapor analyses and forecasts in the lower troposphere. Through forecast error correlation of water vapor and wind in the convective environment of the storm, the errors in wind analyses and forecasts are also reduced and forecasts of the storm’s intensification are improved.

In section 2, the details of Hurricane Ernesto’s genesis and the available observations are described. The assimilation system is discussed in section 3. The analysis increments for wind, temperature, and water vapor due to assimilation of RO refractivity observations using an ensemble filter assimilation system are examined in section 4. The impacts of assimilating the RO data in addition to conventional observation types on analyses and forecasts of the storm’s structure, track, and intensity are presented in section 5. Summary and discussion are given in section 6.

2. Hurricane Ernesto and RO observations

Hurricane Ernesto (2006) was the costliest tropical storm of the 2006 Atlantic season and operational forecasts of the hurricane were unusually diverse. On 18 August a tropical wave moved off the coast of Africa. It tracked westward and associated convection began organizing on 22 August. The next day, convection increased along the wave axis. As it approached the Lesser Antilles, a surface low developed. At 0000 UTC 25 August, Ernesto was classified as a tropical depression of 1007 hPa with maximum winds of 30 kt over the western Atlantic Ocean (13°N, 63°W). It then tracked northwestward and reached tropical storm strength with central surface pressure of 1004 hPa and maximum winds of 35 kt at 2100 UTC 25 August. Ernesto continued to intensify as a tropical storm at 1200 UTC 26 August with a central surface pressure of 997 hPa. It dissipated on 1 September.

<table>
<thead>
<tr>
<th>Table 1. Number of COSMIC RO profiles available in 2-h time windows during 21–26 Aug 2006.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000 UTC</td>
</tr>
<tr>
<td>0200 UTC</td>
</tr>
<tr>
<td>0400 UTC</td>
</tr>
<tr>
<td>0600 UTC</td>
</tr>
<tr>
<td>0800 UTC</td>
</tr>
<tr>
<td>1000 UTC</td>
</tr>
<tr>
<td>1200 UTC</td>
</tr>
<tr>
<td>1400 UTC</td>
</tr>
<tr>
<td>1600 UTC</td>
</tr>
<tr>
<td>1800 UTC</td>
</tr>
<tr>
<td>2000 UTC</td>
</tr>
<tr>
<td>2200 UTC</td>
</tr>
</tbody>
</table>

Fig. 1. Locations of COSMIC radio occultation refractivity profiles at the lowest observed level in the profile (indicated by symbol “N”) over the Atlantic domain on (left) 23 and (right) 24 Aug 2006. The ensemble mean of the 2-h 850-hPa wind forecasts of the ONLY experiment valid at 0600 UTC for each day are also shown. The wind vector unit is m s⁻¹. The hurricane symbol marks the location where Hurricane Ernesto formed as a tropical depression at 0000 UTC 25 Aug 2006.
This study focuses on the period of 21–26 August 2006, from four days before until two days after the formation of the tropical depression. The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC; Anthes et al. 2008; Kuo et al. 2004) RO refractivity profiles have been available since August 2006. There were 178 RO soundings during 21–26 August 2006, approximately 30 profiles per day, in the tropical Atlantic domain (0°–30°N, 30°–100°W). Table 1 shows the time distribution of the RO profiles. Most of the profiles are around 0600 and 1800 UTC. In August 2006, the six COSMIC satellites were not yet fully deployed into their orbits so the number of available RO profiles was still limited and the time distribution of the profiles was not uniform.

The daily spatial distribution of the RO profiles and the ensemble mean of the 2-h wind forecasts of the ONLY experiment (defined in section 4) at 850 hPa and valid at 0600 UTC 23 and 24 August 2006 are shown in Fig. 1. On 23 and 24 August a strong easterly wave developed upstream of the storm and formed a convergent region around 10°N, 40°–60°W. Convection developed in this area, especially on 23 August (Fig. 2). There were several RO profiles in this area on the two days.

3. The assimilation system

A Weather Research and Forecasting model (WRF) ensemble data assimilation system has been under development at NCAR since 2003 (more information available online at www.image.ucar.edu/DAReS; Chen and Snyder 2007; Torn 2010). The Advanced Research version of the WRF model (ARW) and the Data Assimilation Research Testbed (DART) ensemble adjustment Kalman filter (EAKF) system (Anderson 2003, 2007; Anderson et al. 2009) are used to do the assimilation.

The WRF model has a 36-km horizontal resolution grid with 35 vertical levels from the surface to 20 hPa. Physical parameterization schemes include the Kain–Fritsch cumulus scheme, WRF single-moment (WSM) five-class microphysics, the Yonsei University (YSU) boundary layer scheme, and the Noah land surface model.

The EAKF uses observations to update WRF model state (analysis) variables including wind components, temperature, mixing ratio of water vapor, cloud liquid
water, rain, ice and snow, surface pressure, geopotential height, and column mass of dry air. Assimilation of any type of observation can produce increments for all of the analysis variables through the forecast (prior state) ensemble sample covariance.

For example, when one RO refractivity observation is assimilated, the difference between the observation and the ensemble forecast of the observation is used to compute increments for each ensemble estimate of the RO observation. These increments are regressed onto all nearby model variables using the forecast ensemble sample covariance to obtain analysis increments for the state variables. Details of the EAKF analysis procedure can be found in Anderson (2003) and Liu et al. (2008).

In this study, conventional observation types assimilated include radiosonde winds, temperature and moisture; aircraft winds and temperature; surface pressure data, and satellite cloud winds, all obtained from the National Oceanic and Atmospheric Administration (NOAA)–National Centers for Environmental Prediction (NCEP) reanalysis dataset (available online at http://dss.ucar.edu/pub/reanalysis/). The specified observation errors are also obtained from the NCEP dataset.

Observations are assimilated every 2 h in 2-h wide windows centered on 0000, 0200 UTC, etc. This assimilation frequency is higher than used by most operational systems in order to assimilate the temporally irregular satellite observations as effectively as possible. All observations in each 2-h window are assimilated as if they were taken at the center time of the window. The analyses are used to initialize an ensemble of 2-h forecasts for the next analysis time.

The COSMIC Level-2 RO refractivity data is assimilated in this study. In the vertical, all-refractivity observations in a given profile located between a pair of WRF model level interfaces are averaged before assimilation to reduce errors associated with aliasing of small-scale vertical structures in the observations onto larger-scale vertical structures of WRF model refractivity. The averaged RO refractivity observations are then assimilated using a quasi-excess phase operator that horizontally integrates refractivity along a straight line.
path starting from the tangent point up to 18 km above the earth’s surface. The details of the operator are described in Sokolovskiy et al. (2005) and Liu et al. (2008). The assumed phase error is based on the estimation of Chen et al. (2009) and shown in Fig. 3. The analysis grid covers the tropical Atlantic Ocean (0°–30°N, 30°–100°W) as shown in Fig. 1. The initial and boundary ensemble mean conditions for the assimilation are obtained from the 1° × 1° global aviation (AVN) analysis produced by NCEP. The initial and boundary ensemble perturbations are generated by random draws from a distribution with the forecast error covariance statistics of the WRF three-dimensional variational data assimilation (3DVAR) system and then added to the ensemble mean fields (Torn et al. 2006; Barker et al. 2004). The temporally and spatially varying adaptive inflation algorithm of Anderson (2009) is used to inflate the ensemble forecast spreads to make the statistics of prior estimates of observed quantities consistent with the observations. A relatively small ensemble size of 32 is used in this study. To reduce the impact of spurious long-distance covariance estimates, a horizontal and vertical localization (Gaspari and Cohn 1999) is applied to all of the analysis increments from observations. The half-width of the localization is 650 km in the horizontal and 3 km in the vertical; an observation has no impact on a model state variable if it is separated by more than 1300 km horizontally or 6 km vertically.

4. Assimilating only RO refractivity

An experiment assimilating only RO refractivity observations provides a clean way to explore analysis increments of water vapor, temperature, and winds induced by RO refractivity profiles. This experiment (denoted as ONLY in subsequent discussion) extends from 21 to 26 August 2006. For comparison, a parallel experiment assimilating no observations is also done for the same period (NODA run).

Figure 3 shows the excess phase RMS departures of the 2-h forecasts and analyses (ensemble mean) of the ONLY run relative to all of the observed RO refractivity profiles. The departure of the 2-h forecasts (the prior state) is largest in the lower troposphere (much larger than the assumed phase error) and is reduced significantly in the analyses. In the upper troposphere, the forecast error is much smaller (still larger than the assumed phase error) and is reduced less by the assimilation. Almost all
(~98%) of the RO profiles are assimilated in both the lower and upper troposphere.

Next, we examine water vapor, temperature, and wind analysis increments induced by assimilation of the RO refractivity profiles in the environment near the storm. We focus on 23 and 24 August, the two days before the genesis of tropical depression Ernesto at 0000 UTC 25 August. Figure 4 shows the daily analysis increments of water vapor at 700 and 250 hPa. Several RO profiles are available in the vicinity and upstream of the storm (5°–15°N, 40°–70°W). In general, the increments are limited to the neighborhood of the RO profiles and spread to about 1200 km in diameter, consistent with the horizontal cutoff distance. The maximum analysis increments are not exactly collocated with the RO profiles and the increments are generally not circular in shape. This is because the increments are determined by the multivariate covariance of the RO refractivity at the RO data locations with water vapor at nearby model grid points and this depends strongly on details of the synoptic situation.

On 23 August, two RO refractivity soundings were located upstream of the storm’s genesis area. One was at 0510 UTC, 9.4°N, 52.3°W, and penetrated down to 960 m; the other was at 0636 UTC, 9.5°N, 52.5°W, and penetrated down to 560 m. At these two RO sounding locations, there is an area where water vapor is increased with a maximum of 0.6 g kg⁻¹ at 700 hPa.

There is also one RO refractivity profile (0711 UTC 23 August, ~13.3°N, 66°W) very close to the location where Hurricane Ernesto formed as a tropical depression about two days later at 0000 UTC 25 August. This profile penetrated down to the surface. At this profile’s location, water vapor is increased with a maximum of 0.9 g kg⁻¹ at 700 hPa. At 250 hPa, water vapor increments are generally small with a maximum of 0.015 g kg⁻¹.

On 24 August, two almost collocated RO profiles were again located upstream of the storm near 0508 UTC 11.4°N, 54.9°W. These two profiles penetrated down to 700 and 200 m above the surface respectively. At the profiles’ location, there is an area where water vapor is increased even more with a maximum of 1.8 g kg⁻¹ at
At 700 hPa, water vapor increases are also larger with a maximum of 0.03 g kg\(^{-1}\) in the area.

The daily temperature analysis increments are shown in Fig. 5. In general, the temperature increments have opposite signs from the water vapor increments, consistent with the definition of RO refractivity. On 23 August, the temperature increments are small. For instance, the temperature increment is about \(-0.2\) K at 700 hPa at the two RO sounding locations upstream of the storm and about \(-0.4\) K at 250 hPa. On 24 August, the temperature increments are slightly larger, about \(-0.6\) K at both 700 and 250 hPa upstream of the storm’s genesis area. The small temperature increments in the lower troposphere suggest that the RO refractivity is more strongly related to water vapor in the lower troposphere of the tropics.

Figure 6 shows the wind analysis increments at 700 and 250 hPa. The RO soundings induce significant wind increments in both the lower and upper troposphere in the vicinity of the observation locations. The maximum flow speed increment is 5 m s\(^{-1}\) on 23 August and 10 m s\(^{-1}\) on 24 August upstream of the storm’s genesis area. The RO profiles upstream of the storm induce a divergent flow increment at 250 hPa. This suggests the analysis will be more favorable to development of convection. The large wind increments are also consistent with those for temperature and water vapor and make the analyses more balanced, reducing the noise in the subsequent forecasts.

The RO profiles in the vicinity of the storm were all observed around 0600 and 0700 UTC. The analysis increments from RO data assimilation are then propagated by the forecast model until the time when a tropical depression formed at 0000 UTC 25 August. Figure 7 shows the 2-h forecast difference of water vapor between the ONLY run and NODA run at 700 hPa. The additional water vapor in the ONLY run propagates to the storm’s genesis area and is enhanced in magnitude and size. At 0000 UTC 25 August, the water vapor is \(3\) g kg\(^{-1}\) greater than in the NODA run and covers a much larger area with diameter about 1500 km in the storm’s genesis area.

Wind analysis increments are also propagated into the storm’s genesis area and enhanced (Fig. 8). At 0000 UTC 25 August, a cyclonic circulation with a speed of about 5 m s\(^{-1}\) forms at 700 hPa and a strong large-scale anticyclonic circulation with a speed of about 10 m s\(^{-1}\) develops at 250 hPa in the storm’s genesis area. These adjustments to the large-scale wind environment favor the development of the storm, as shown below.

Note that there were no RO profiles near 0000 UTC 25 August in the domain (Table 1). All impacts from the RO data at this time come from observations at previous analysis times that have evolved through the model forecasts.

Next, we explore the contribution of the RO data in the lower troposphere to the analysis increments and forecast differences for water vapor and wind in the storm’s genesis area. The hypothesis is that the RO refractivity data in the lower troposphere has mostly water vapor information and can be strongly related to the winds of both the lower and upper troposphere, especially in
moist convectively active environments. When the RO refractivity in the lower troposphere is ignored, the impact from the assimilation of RO data can be significantly reduced.

Figures 9 and 10 show the water vapor and wind increments from assimilating only the RO data above 6 km for 23 and 24 August 2006 (referred to subsequently as the ONLY6-km run). The water vapor increments at 700 hPa are much reduced and the wind increments at 700 hPa almost completely disappear. In particular, the divergent flow at 250 hPa upstream of the storm on 23 August completely disappears.

The divergent flow at 250 hPa upstream of the storm on 24 August, however, is only slightly weakened because the convection is much weaker in this area at 0600 UTC 24 August (cf. Fig. 2). This suggests that the
large wind analysis increments at 250 hPa mainly come from assimilation of RO profiles in the upper troposphere.

In the 2-h forecast valid at 0000 UTC 25 August, the added water vapor from RO data assimilation is reduced from 3 to 0.9 g kg\(^{-1}\) in the ONLY 6-km run in the storm’s genesis area (Fig. 11). The cyclonic circulation at 700 hPa completely disappears and the large-scale divergent flow at 250 hPa is much reduced (Fig. 12).

These results suggest that assimilation of RO refractivity below 6 km contributes strongly to the water vapor and wind adjustments in the lower troposphere as well as the divergent flow adjustments in the upper troposphere in the convectively active area. These adjustments occur through the correlation of water vapor and wind in the lower and upper troposphere with RO refractivity in the lower troposphere at the RO profile locations. The wind increments are consistent with the dynamics of moist convection in the convectively active area; that is, more moisture in the lower troposphere provides more fuel to the convection and so enhances convergent circulation in the lower and divergent circulation in the upper troposphere. This also means that the multivariate forecast error covariance estimated from the ensemble forecasts is realistic and captures the key features of the moist convective environment.

Fortunately, there were many special dropsonde observations in the domain during the storm’s genesis. To examine if the analysis increments and forecasts are good, the 2-h forecasts of water vapor, temperature, and winds from the ONLY, ONLY 6-km, and NODA run are validated against the dropsondes and radiosondes in the domain during the period of 21–26 August. The RMS forecast error for water vapor is reduced a bit in the lower troposphere. For instance, at 850 hPa, the error is reduced from 2.3 to 2.1 g kg\(^{-1}\), an approximately 10% error reduction. This is quite significant given the fact that water vapor is quite uniformly distributed in the horizontal in the tropics. The impact of RO data on the forecast temperature error of the ONLY run is small and mixed (Fig. 13). The temperature errors are slightly larger at some levels when all the RO data are assimilated. One possible reason could be the sampling errors from the relatively small
ensemble size used in this study. With a larger ensemble size, the small degradations might disappear or become smaller.

One interesting finding is that the wind RMS error of the ONLY run is reduced, especially in the upper troposphere. For instance, at 200 hPa, the error of the ONLY run is reduced from 11.1 m s\(^{-1}\) for the NODA run to 8.3 m s\(^{-1}\).

When only the RO data above 6 km is assimilated, the water vapor and wind error reduction in the upper troposphere are only about half as large as for the ONLY run. This again suggests that assimilation of RO refractivity observations in the lower troposphere contributes to the error reduction in the upper troposphere in the convective environment.

5. Impact of RO data on analyses and forecasts of the storm’s genesis

This section discusses the impact of RO observations on analyses and forecasts of the storm’s structure when conventional observation types are also assimilated. Three experiments are performed: 1) the control run (CTRL) assimilates radiosonde temperature, winds, and specific humidity, aircraft winds and temperature, satellite cloud drift winds, and surface station pressure observations; satellite infrared and microwave sounders, radiances, and images are not assimilated; 2) the RO run adds the RO profiles; 3) the RO 6-km run adds the RO refractivity profiles above 6 km only. The purpose of the third experiment is to examine if the RO profiles in the lower troposphere have major impacts considering that at least some operational systems assimilate only upper-level RO profiles (e.g., above 6-km height). These assimilation experiments start at 0000 UTC 21 August and end at 0000 UTC 27 August.

Analyses of sea level pressure and relative vorticity at 1000 hPa at 0000 UTC 25 August are shown in Fig. 14. The CTRL analysis has a weak depression with a minimum pressure of 1010 hPa. The depression in the RO 6-km analysis is 1009 hPa and the one in the RO analysis has the strongest intensity of 1008 hPa, closer to the observation of 1007 hPa. In addition, the CTRL analysis has a distorted vortex with maximum
vorticity of $2.0 \times 10^{-4}$ s$^{-1}$ and two separate centers. The RO 6-km and RO analyses have a stronger and less distorted vortex with a single center with maximum vorticity of $4.0 \times 10^{-4}$ s$^{-1}$. The vortex from the RO analysis is less distorted than the analysis from RO 6 km.

The ensemble mean 48-h forecast of the storm’s central sea level pressure and track initialized at 0000 UTC 25 August are shown in Fig. 15. The storm in the CTRL forecast intensifies much more slowly than observed and reaches only 1005 hPa at 0000 UTC 27 August, about 10 hPa weaker than observed. The RO 6-km forecast shows more realistic intensification, and the RO forecast is even better. The track errors of the storm in the RO forecast are slightly [−(30–50) km] smaller than the CTRL forecast. The track errors of the storm in RO 6-km the forecast are a bit smaller on the first day but a bit larger (≈50 km) than the CTRL forecast track errors in later days. In general, given the BEST track positioning error of −(100–150) km for weak tropical storms like this, the differences between the RO 6-km, CTRL, and RO track position errors do not appear to be significant. The impact of the assimilation of RO data on the development of the storm is also visible in the total column cloud liquid water of the forecast, which is compared with the satellite IR cloud image in Fig. 16.

6. Summary and discussion

This study explores how radio occultation refractivity observations impact analyses and forecasts of Hurricane Ernesto’s genesis using an ensemble assimilation system. Assimilation of RO refractivity data in the vicinity of the storm adds more water vapor in the lower troposphere to the analyses. The RO data also introduces wind analysis increments in both the lower and upper troposphere, consistent with the convective environment. The temperature analysis increments created by the RO data are relatively small.

The water vapor and wind analysis adjustments are propagated by model forecasts into the storm’s genesis area and enhanced generating a wider and wetter environment. They also produce a large-scale cyclonic circulation in the lower troposphere and a large-scale divergent flow in the upper troposphere, leading to more accurate analyses of the later stages of the genesis of the storm. The root-mean-square errors of water vapor and wind forecasts compared to dropsonde and radiosonde observations are reduced consistently. When only the RO profiles in the upper troposphere (above 6 km) are assimilated, the major impact of the RO data disappears suggesting the importance of assimilating the RO data in the lower troposphere. Analyses and forecasts of the storm’s intensification are improved when the RO profiles are assimilated. These results suggest that RO refractivity data has potential to improve analyses and forecasts of tropical cyclones using ensemble assimilation systems.

The positive impact of the RO data on this storm appears to depend on the water vapor and wind errors of the forecasts and the availability of RO profiles in the
vicinity of the storm. As a result, the impacts of RO data on other tropical storms may vary. Further study with more tropical cyclone cases (e.g., all of the major typhoons during 2008) is underway and preliminary results show that COSMIC RO profiles have positive impact on the analyses and forecasts of all the typhoons. These results will be reported separately.

In this study, the satellite infrared and microwave sounders and images are not used. The results obtained here may be limited to the specific configuration of the WRF/DART ensemble assimilation system. We plan to add satellite sounder and image data including total precipitable water from Special Sensor Microwave Imager (SSM/I) in the control analyses and reevaluate
the impact of RO data on analyses and forecasts of tropical storms.

Acknowledgments. The authors thank Drs. Rick Anthes, Chris Snyder, Ryan Torn, Yongsheng Chen, and Glen Romine for their encouragement and valuable help with this study. The research results presented in this paper are supported by the National Science Foundation under Awards ATM-0410018 and INT-0129369, and the National Aeronautics and Space Administration under Grant NNX08AI23G. The National Center for Atmospheric Research is sponsored by the National Science Foundation. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author and do not necessarily reflect the views of the National Science Foundation.
Fig. 14. (left) Ensemble mean sea level pressure and (right) relative vorticity analyses (top) without RO refractivity data (CTRL run), (middle) with the RO profiles above 6 km only (RO 6-km run), and (bottom) with all of the RO data (RO run) at 0000 UTC 25 Aug 2006. The hurricane symbol indicates the observed position for Ernesto. Units: (left) hPa and (right) $1.0 \times 10^{-4}$ s$^{-1}$.
FIG. 15. Ensemble mean of 48-h forecasts of Ernesto’s (top) central sea level pressure (hPa) and (bottom) track error (km) initialized from the analyses at 0000 UTC 25 Aug 2006.

FIG. 16. The ensemble mean of the total column cloud liquid water of the 48-h forecasts initialized from the RO, RO 6-km, and CTRL analyses at 0000 UTC 25 Aug 2006. Units: log(kg kg$^{-1}$). The observations of the actual storm are from satellite IR cloud images.
REFERENCES


