Impact of Satellite-Derived Rapid-Scan Wind Observations on Numerical Model Forecasts of Hurricane Katrina

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ABSTRACT

The impacts of special Geostationary Operational Environmental Satellite (GOES) rapid-scan (RS) wind observations on numerical model 24–120-h track forecasts of Hurricane Katrina are examined in a series of data assimilation and forecast experiments. The RS wind vectors are derived from geostationary satellites by tracking cloud motions through successive 5-min images. In these experiments, RS wind observations are added over the area 15°–60°N, 60°–110°W, and they supplement the observations used in operational forecasts. The inclusion of RS wind observations reduces errors in numerical forecasts of the Katrina landfall position at 1200 UTC 29 August 2005 by an average of 12% compared to control cases that include “targeted” dropsonde observations in the Katrina environment. The largest average improvements are made to the 84- to 120-h Katrina track forecasts, rather than to the short-range track forecasts. These results suggest that RS wind observations can potentially be used in future cases to improve track forecasts of tropical cyclones.

1. Introduction

Improving the forecast of tropical cyclone (TC) tracks remains a challenging problem in numerical weather prediction. During the 2005 season, for example, the Navy Operational Global Atmospheric Prediction System (NOGAPS) provided 72-h forecasts with average track errors of about 170 n mi for TCs in the Northern Hemisphere—this compares to average track errors of about 220 n mi in 2000 (Goerss et al. 2004). The improved TC track forecasts available today are largely because of increases in the amount and quality of observations as well as improvements in forecast models and data assimilation procedures (Goerss and Hogan 2006). The use of multimodel ensembles for “consensus forecasts” is also providing improved guidance to forecasters for TC track prediction (Goerss 2000). However, significant societal and economic value can still be gained by additional increases in the accuracy of track forecasts for landfalling tropical cyclones.

In recent years, the use of “targeted observations” to improve numerical forecasts of significant weather events, including TCs, has been examined in a series of field programs (Langland 2005 provides an overview of targeting programs and references). The process of targeted observing for the atmosphere involves methods to identify “sensitive” locations of the atmosphere in which addition of special observations is expected to improve the analysis and forecast of a weather event (Majumdar et al. 2006; Wu et al. 2007a). The special targeted observations,
along with regular observations, are ingested into operational data assimilation procedures to produce improved initial conditions for deterministic and ensemble forecast products. In TC cases, the most commonly used approach for targeted observing thus far has been the use of manned reconnaissance aircraft to deploy sets of 10–40 dropsondes in targeted observation regions. In a majority of cases, these dropsondes have produced measurable improvements in track forecast skill (Aberson 2003, 2008; Wu et al. 2007b; Chou and Wu 2008).

Satellite-derived observations may also be used in a targeted mode to improve forecasts, and have the potential to provide beneficial forecast impacts beyond that obtained from targeted dropsondes. The advantages of using satellite observations for targeting include the larger numbers of observations that can be provided, the ability to observe widely separated components of “target regions,” and the higher temporal frequency of coverage. In this study, we examine the impact of rapid-scan (RS) wind observations (Velden et al. 2005) generated from the Geostationary Operational Environmental Satellite (GOES) on track forecasts of Hurricane Katrina. We do not study the impact of satellite wind data on predicted hurricane intensity, since the resolution of the forecast model (T239 spectral truncation, equivalent to about 0.5° latitude and longitude, and 30 vertical levels) is not adequate to represent the hurricane inner core and the eyewall structure changes that are involved in intensity forecasting. The impact of RS winds in mesoscale model forecasts of tropical storms is described by Pu et al. (2008).

In section 2, the procedure for deriving the RS winds is presented. A series of data assimilation and forecast experiments using NOGAPS and the Naval Research Laboratory (NRL) Atmospheric Variational Data Assimilation System (NAVDAS) will be described in section 3. NOGAPS (Hogan and Rosmond 1991) is a primitive equation spectral model with a complete set of moist physics, including an Emanuel cumulus parameterization (Hogan and Pauley 2006). NAVDAS (Daley and Barker 2001) is a three-dimensional variational data assimilation (3DVAR) system that is run in a 6-h cycle and provides analyzed fields of temperature, wind components, and humidity on a 0.5° latitude and longitude grid and 60 pressure levels from the surface to 0.1 hPa. The results of the experiments are discussed in section 4, and a summary is provided in section 5.

2. Geostationary satellite rapid-scan wind observations

Wind observations derived from geostationary satellite imagery (Velden et al. 2005) are a primary component of the global observing system that supports operational numerical weather prediction (Saunders and English 2006). Approximately 90 000 satellite-derived wind “super-ob” vectors are assimilated in NAVDAS every 6 h. Also called atmospheric motion vectors (AMVs), these observations are the only regular source of wind observations in the free atmosphere over most of the world’s oceanic areas, including TC development regions (Goerss et al. 1998). AMV observations are provided where traceable cloud or water vapor features exist, at levels from the near surface to about 100 hPa.

Routine, operational, AMVs are generated from successive 30-min images, using infrared (IR), shortwave IR, water vapor (WV), and visible (VIS) channels. Special RS modes allow for more-frequent satellite imagery, which has been shown to improve the tracking capability of short-lived cloud features. Consequently, a higher quality and higher density of AMVs will pass the producer’s quality control procedures (Velden et al. 2005). The optimal image time interval for generating RS winds varies by spectral channel. Studies have shown that the shortwave IR, longwave IR, and VIS channels benefit most from the increased temporal resolution (Velden et al. 2000), and thus are the only such observations included in these experiments.

A procedure to construct super-ob wind observations is used with both the operational AMVs and the RS-winds prior to the NAVDAS assimilation process. In general, the super-ob wind vectors are constructed by averaging all available winds in areas of about 200 by 200 km. At least two wind observations are required to make a superob, although more can be used. Whereas the original AMV wind observations may be separated by 12 km, the horizontal spacing between adjacent superob wind vectors is generally 2° of latitude, or as low as 1° in regions of strong wind shear. The superobs are constructed from winds that are closest to the analysis time, and the winds must be within a 1-h time window to form a super-ob (for additional details see Pauley 2003). The super-ob procedure acts as a filter that reduces the data density and also reduces the uncorrelated error (Berger and Forsythe 2004). In NAVDAS, the assumed observational error of the assimilated AMV super-ob is a step function of pressure and is specified as 2.8 m s⁻¹ below 850 hPa, 4.4 m s⁻¹ from 400 to 700 hPa, and 5.2 m s⁻¹ above 300 hPa.

Other satellite observations assimilated by NAVDAS include radiance observations from IR sounders, surface wind vector estimates from scatterometers, wind speed estimates from Special Sensor Microwave Imager (SSM/I), and satellite-derived total precipitable water estimates. The primary sources of in situ atmospheric observations are radiosonde profiles, surface data from
land and ship surface stations and buoys, and commercial aircraft data. In addition, synthetic (bogus) TC vortex observations (Goerss and Jeffries 1994) are assimilated in the Hurricane Katrina analyses from 0000 UTC 25 August to 1800 UTC 28 August 2005. The TC bogus observations include temperatures and winds at levels from 400 to 1000 hPa, in a pattern of 13 grid points that extend as far as 300 km from the center of Hurricane Katrina. The TC bogus wind observations are assigned observation errors that are roughly half as large as those assigned to AMV wind super-obs at similar pressure levels.

3. Experimental design

To test the model forecast impact of the RS winds, we designed four experiments, summarized in Table 1. In all experiments, satellite wind observations are assimilated as super-obs. The control forecast (CNO) uses

<table>
<thead>
<tr>
<th>Expt</th>
<th>Configuration of operational AMVs</th>
<th>Configuration of RS wind observations, which replace regular winds in the area 15°–60°N, 60°–110°W</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNO</td>
<td>Operational configuration—No AMVs over land</td>
<td>None</td>
</tr>
<tr>
<td>CNL</td>
<td>As in CNO, plus operational AMVs over land areas</td>
<td>None</td>
</tr>
<tr>
<td>RS1</td>
<td>As in CNO</td>
<td>Use observations only at exact analysis time (0000, 0600, 1200, and 1800 UTC)</td>
</tr>
<tr>
<td>RS2</td>
<td>As in CNO</td>
<td>Use observations at any time in the ±3-h analysis window</td>
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</tbody>
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FIG. 1. Regular geostationary (blue) and RS geostationary (red) wind super-obs used to produce the NAVDAS analysis at 0000 UTC 27 Aug 2005. Wind barbs show direction and speed (m s\(^{-1}\)). The area in which the RS winds are provided and replace the regular winds is 15°–60°N, 60°–110°W. The 6-h time window for the regular wind observations is 2100 UTC 26 Aug–0300 UTC 27 Aug 2005, and the RS winds (in experiment RS1) are observations at 0000 UTC 27 Aug 2005. Wind observations at all vertical levels are shown in the figure. The best analysis positions of Katrina at 12-h intervals from 1200 UTC 24 Aug to 1200 UTC 29 Aug 2005 are shown as solid green dots, and the position at this analysis time is shown as a black dot.
only the regular (e.g., “operational”) satellite wind data (AMVs), and no AMVs are used over the land area of North America. In a variation of the control, called experiment CNL, we also assimilate the operational AMVs over the United States, Mexico, and Canada.

There are two assimilation and forecast experiments using the RS wind observations derived from GOES-12 imagery. In RS1, we replace all operational AMVs in the region 15°–60°N, 60°–110°W (Fig. 1) with RS wind observations, over both ocean and land surfaces. The super-obs of RS winds in RS1 use only observations within one hour of the analysis times (0000, 0600, 1200, or 1800 UTC). In experiment RS2, we again use RS winds to replace the operational AMVs in the region 15°–60°N, 60°–110°W. However, in RS2, the super-obs use RS winds at any time during the 6-h assimilation window, in the same way that super-obs are constructed for the operational forecast. For example, the RS2 analysis at 1200 UTC uses observations between 0900 and 1500 UTC. The mean number of RS wind vectors provided each hour in the region 15°–60°N, 60°–110°W for these experiments is about 29 000.

Figure 2 shows the distribution of RS winds used in the RS1 analysis at 0000 UTC 27 August 2005 over the Hurricane Katrina development region. Also shown in Fig. 2 are the locations of 15 dropsondes deployed by the National Oceanic and Atmospheric Administration (NOAA) aircraft within ±3 h of this analysis time that were targeted to improve the Katrina forecast. It is noted that similar-size sets of dropsonde observations were included in every analysis from 0000 UTC 25 August to 1800 UTC 28 August 2005. The inclusion of these dropsonde observations adds considerable information to the analyses in the vicinity of Katrina, which may reduce the additional benefit obtained from the special RS wind observations.

Figure 2 shows the distribution of RS geostationary wind super-obs at all levels used to produce the NAVDAS analysis at 0000 UTC 27 Aug 2005 for experiment RS1. The best analysis positions of Katrina at 12-h intervals from 1200 UTC 24 Aug to 1200 UTC 29 Aug 2005, are shown as solid dots, and the position at this analysis time is the dot within a square. The locations of dropsondes between 1800 UTC 26 Aug and 0300 UTC 27 Aug 2005 that were targeted to improve the Katrina forecast are shown as solid X symbols.

The large region over which the RS wind observations are provided is intended to include smaller (synoptic-scale) “target areas” where improved initial conditions are likely required to make more accurate track forecasts of Hurricane Katrina. At certain times, the observation target areas for hurricanes making landfall in the eastern United States can be well upstream over North America, related to eastward-propagating synoptic features (Peng
et al. 2007). An example of an observation target region over the central United States in a 48-h forecast of Hurricane Katrina appears in Fig. 1 of Langland (2005).

4. Results of forecast experiments

The landfall of Hurricane Katrina was just east of New Orleans at about 1200 UTC 29 August 2005. A timeline of the forecast experiments is shown in Fig. 3. To spin up the background fields we begin the data assimilation cycling at 0000 UTC 20 August 2005. Forecasts are made starting at 1200 UTC 24 August (120-h forecast), and subsequently at 12-h intervals, with the last forecast starting at 1200 UTC 28 August 2005 (24-h forecast). Thus, forecasts are started from 9 analysis times, and a total of 36 forecasts were produced in the 4 experiments.

The track (distance) errors in the Katrina landfall forecasts are summarized in Fig. 4. Each of the RS1 and CNL Katrina forecast tracks, along with the best analyzed track for the storm, appear in Fig. 5. The control forecasts that use only operational AMV observations (CNO and CNL) have track forecast skill that is better than the NOGAPS basin average at all forecast lengths except for the 108-h forecast. Although the 120-h CNO forecast has a track error of only 35 n mi, this is considered an anomaly that is not representative of typical model predictive capability. Similar patterns in consensus forecasts for Katrina are shown by Goerss (2006).

The 108–24-h CNO and CNL forecasts are essentially identical in terms of track forecast skill, which indicates that addition of operational AMVs over land has little impact on the NOGAPS Katrina forecasts. However, the effect of adding the higher-quality and higher-density RS winds in experiments RS1 and RS2 produces some significant improvements to the NOGAPS landfall forecasts (Fig. 4). The RS1 (RS2) forecasts, provide about a 12% (9%) decrease in track error compared to CNL if the track error differences of all nine forecasts are averaged. Notably, no forecasts are degraded by addition of the RS winds.

An interesting result is that the RS1 forecasts, which use RS wind observations within 1 h of the analysis time, are slightly superior to the RS2 forecasts, which include observations from various times within the 6-h analysis window. Thus, the “off-time” wind observations in experiment RS2 do not improve the analyses to the same extent as the “close-to-analysis-time” observations. This result may occur because NAVDAS and other 3DVAR procedures use simplified linear approximations to account for changes in the first-guess (background forecast) between analysis times.

Note that the differences in the analyses between the RS wind experiments (RS1, RS2) and the control cases (CNO, CNL) are not due solely to the addition of RS wind observations at a single analysis time. Rather, the differences are an accumulation of information from observations added at earlier analysis times, which can propagate from any part of the RS wind observing domain. The influence of earlier observations is transmitted through the data assimilation cycle, which updates the analysis every 6 h by combining information from a previous short-range forecast (the “background”) with the new observations.

Finally, we quantify the track errors from all the CNL and RS1 forecasts, averaged by forecast length, illustrated in Fig. 6. Note, these results now include forecasts verifying at all times (not just the landfall verification forecasts) during the experiment period. This reveals that assimilation of RS winds makes the largest improvements to medium-range forecasts, between 84 and 120 h. This result is significant because it suggests that medium-range forecasts of hurricane track may be
sensitive to observations in areas far removed from the storm itself. Thus, targeting of observations to improve the hurricane track may benefit from of large target areas such as the RS wind domain shown in Fig. 1 and used in this study.

5. Summary

A potential new approach for targeted observing has been demonstrated, that involves the assimilation of satellite RS wind observations (RS winds) over a large area during the development of a major hurricane. The key aspects of this approach to targeting are (i) starting the assimilation of the RS wind observations several days in advance of the critical hurricane landfall forecasts; and (ii) providing the RS wind observations over a region that is large enough to include localized areas of maximum dynamic sensitivity (observation “target areas”) that evolve and move with the synoptic flow during the hurricane development. Assimilating the RS winds for several days prior to the landfall forecasts allows the RS wind observations to gradually improve the quality of the atmospheric analyses that are used as initial conditions for the model forecasts. In addition, the RS winds can improve the analysis in regions that may be logistically difficult to survey with dropsondes from reconnaissance aircraft.

While this set of nine forecast times is a relatively small sample size, the identified improvements in Katrina landfall forecast skill are encouraging in terms of RS wind value. The positive impact of the RS wind observations is notable, especially as it is compared with
above-average skill of the control forecasts, which benefited from large numbers of dropsondes over the Gulf of Mexico that were targeted specifically to improve forecasts of Hurricane Katrina. It is hoped that the use of RS satellite wind observations for targeted improvement of tropical cyclone forecasts may mitigate some of the problems reported with dropsonde-based targeting—specifically the occurrence of forecast degradation reported in some cases (Aberson 2008).

Yet, these experiments using 3DVAR are not optimal for demonstrating the full value of RS wind observations. For example, experiment RS1 uses less than 20% of the total RS wind observations that were provided, due to the inability of 3DVAR methods to assimilate observations at hourly intervals in an optimal manner. It is expected that additional forecast benefit will be shown in experiments using 4DVAR procedures that can use a larger fraction of the RS wind observations, and also with the use of expected error information for the RS winds (Berger and Velden 2006).

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