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Improved hurricane track and intensity forecast using single field-of-view advanced IR sounding measurements

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[1] Hyperspectral infrared sounders such as the AIRS and IASI provide unprecedented global atmospheric temperature and moisture soundings with high vertical resolution and accuracy. The AIRS and IASI data have been used in global numerical weather prediction models with positive impact on weather forecasts. The high spatial resolution single field-of-view soundings retrieved from AIRS have been applied to hurricane track and intensity assimilations and forecasts. The newly developed NCAR WRF/DART ensemble data assimilation is performed at 36 km resolution. Studies show that the track error for Hurricane Ike (2008) is reduced greatly when AIRS soundings are used compared with the control run which includes other observations such as radiosonde, satellite cloud winds, aircraft data, ship data, and land surface data, etc. The hurricane intensity forecast is also substantially improved when AIRS data are assimilated. This study demonstrates the importance of high spatial and hyperspectral IR sounding data in forecasting hurricanes.
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1. Introduction

[2] Accurate analyses or initialization of tropospheric water vapor and temperature are crucial for forecasts of tropical cyclones. The vertical and horizontal structure of water vapor and temperature determines the degree of atmospheric instability and controls locations of meso-scale convective development. The water vapor distribution is especially important for the genesis and development of tropical cyclones [*Gray*, 1968; *Palmen*, 1948; *Riehl*, 1948; *Mcbride and Zehr*, 1981]. Satellite observations are the principal source of information about water vapor and temperature over the tropical oceans where conventional in situ observations are relatively sparse. Advanced InfraRed (IR) sounder data such as Atmospheric InfraRed Sounder (AIRS) and Infrared Atmospheric Sounding Interferometer (IASI) have provided unprecedented temperature and moisture profiles with high vertical resolution and accuracy. Although the Advanced Microwave Sounding Unit (AMSU) provides soundings in most cloud coverage, the advanced IR sounders can provide soundings with better vertical resolution and accuracy with higher spatial resolution (12–14 km at nadir), which are very important for regional numerical weather prediction (NWP). The Cooperative Institute for Meteorological Satellite Studies (CIMSS) of University of Wisconsin-Madison has developed a method to derive temperature and moisture profiles from advanced IR radiance measurements alone in clear skies and some cloudy sky conditions on a single field-of-view (SFOV) basis [*Li and Huang*, 1999; *Li et al.*, 2000; *Zhou et al.*, 2007; *Weisz et al.*, 2007]. This research product using the CIMSS hyperspectral IR sounder retrieval (CHISR) algorithm provides AIRS soundings with higher spatial resolution (approximately 13.5 km) than the operational AIRS sounding product [*Susskind et al.*, 2003] with a spatial resolution of 50 km at nadir. This enhanced resolution of IR soundings can be useful for initialization of meso-scale storm forecasts, including tropical cyclones.

[3] The advanced IR sounder radiance measurements have shown positive impact on global numerical weather prediction (NWP) [*Le Marshall et al.*, 2006]. However, the satellite-based sounding data have not been widely assimilated in regional meso-scale forecast models for forecasting extreme weather, like tropical storms. The maturing advanced ensemble based data assimilation systems are particularly useful for understanding the use of soundings, especially the water vapor soundings from advanced IR sounders in hurricane forecasts because the ensemble based systems use explicitly flow- and time- dependent full forecast error covariances; consequently, the corrections from the observations are also flow- and time- dependent. In particular, the water vapor observations can make consistent adjustments to other model variables according to the forecast covariance [*Liu et al.*, 2007].

[4] Research has been carried out to evaluate the impact of high spatial resolution (13.5 km for AIRS) IR soundings developed at CIMSS on tropical storm forecasts. We have applied the high spatial resolution SFOV soundings retrieved from AIRS using the CHISR algorithm to the hurricane track and intensity assimilation and forecast with the NCAR (National Center for Atmospheric Research) WRF/DART (Weather Research and Forecasting/Data Assimilation Research Testbed) ensemble assimilation system [*Anderson*, 2003; *Anderson and Collins*, 2007] (www.image.ucar.edu/~DAReS/). Studies show that the track error for Hurricane Ike (2008) is reduced greatly when AIRS SFOV soundings are used compared with the control run which includes other observations such as radiosonde, satellite cloud winds, aircraft data, ship data, and land surface data. The hurricane intensity forecast is also substantially improved by 10 $\sim$ 20 hPa after 24 hours when the AIRS SFOV soundings are assimilated. In order to compare the impact of AIRS with AMSU (also on Aqua) which has low spatial and vertical resolutions, the operational AMSU only temperature soundings are also tested in the assimilation. The

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AMSU temperature soundings provide a much smaller impact on hurricane assimilation than the AIRS. This study demonstrates the potential applications of high spatial and vertical resolution soundings from advanced IR sounders in forecasting the intensity and track of hurricanes.

2. CIMSS Hyperspectral IR Sounder Retrieval

[5] The CIMSS hyperspectral IR Sounder Retrieval (CHISR) algorithm has been developed to retrieve atmospheric temperature and moisture profiles from advanced IR sounder radiance measurements alone in clear skies and some cloudy sky conditions on a single field-of-view (SFOV) basis [*Li and Huang*, 1999; *Li et al.*, 2000; *Zhou et al.*, 2007; *Weisz et al.*, 2007]. The algorithm has three steps: the first step is the IR sounder sub-pixel cloud detection using a high spatial resolution imager cloud mask product (for example, the AIRS cloud mask can be derived from the MODIS cloud mask [*Li et al.*, 2004], while the Advanced Very High Resolution Radiometer (AVHRR) cloud mask can be used for IASI cloud detection); the second step is to perform an eigenvector regression on the hyperspectral IR radiance measurements for a first guess of temperature and moisture profiles; and the final step is to update/improve the first guess by performing a one-dimensional variational (1DVAR) retrieval algorithm with a Quasi-Newton iteration technique. Radiance measurements from all IR channels are used in the sounding retrieval process. This CIMSS research product provides AIRS soundings with higher spatial resolution of approximately 13.5 km than the operational AIRS sounding product which is based on the AMSU/AIRS cloud-clearing algorithm [*Susskind et al.*, 2003]. The operational sounding product has a spatial resolution of approximately 50 km at nadir, which is much coarser than the resolution of most regional hurricane forecast models. The CIMSS spatial resolution enhanced temperature and moisture soundings from an advanced IR sounder in a hurricane environmental region can be assimilated in hurricane models for track and intensity forecasts.

3. Assimilation Method

[6] DART uses the advanced Ensemble Adjustment Kalman Filter (EAKF) [*Anderson*, 2003] to blend the observations with WRF short-range forecasts (first guess) to create the analysis. Assuming observational error distributions are independent for each scalar observations, observations can be assimilated sequentially in any order in DART. More detailed descriptions are given by *Anderson* [2003] and *Liu et al.* [2008, The benefits of radio occultation observations to the analysis of the genesis of hurricane ernesto, submitted to *Monthly Weather Review*, 2009]. One challenge for data assimilation at the meso-scale is that the background/forecast covariances between observations and model state variables are generally not well known, especially in the tropics. These covariances vary significantly with time and space, and it is not well represented by any static covariances. DART employs a set (ensemble) of model short-range forecasts valid at the analysis time to generate covariances between model state variables (such as water vapor and temperature) and the observations. It was shown that these ensemble based correlations can lead to better analyses of water vapor and temperature in assimilation of satellite water vapor related measurements [*Liu et al.*, 2007]. To reduce the noise in the sample covariance estimates for the observations with physically distant model state variables, a horizontal localization with half-width of 650km is applied. In addition, advanced ensemble based adaptive ensemble inflation [*Anderson*, 2007] is applied to maintain the ensemble spreads at a reasonable level and reduce the impact of model system errors.

4. Hurricane Case

[7] Hurricane Ike (2008) formed as a tropical depression of 1005 hPa with maximum winds of 30 knots over the western Atlantic Ocean (39.5°W, 17.6°N) at 1500 UTC on 1 September 2008. It moved mainly westward and reached Category-1 strength with a central surface pressure of 984 hPa and maximum winds of 70 knots at 2100 UTC on 03 September. Ike continued to intensify to Category 3 at 00 UTC on 06 September with a central surface pressure of 958 hPa near (64.7°W, 22.8°N), ~500 km off Cuba. At 00 UTC on 08 September, Ike was located at (75.2°W, 21.1°N).

5. Assimilation Experiments With AIRS SFOV Soundings

[8] In our two-step experiments, a 48-hour assimilation is run first and then followed by a 96-hour forecast. The assimilation of the observations starts at 00 UTC on 06 September 2008 and continues cycling every 6-hour until 00 UTC on 08 September 2008. That is, after the cold start with an initial ensemble at 00 UTC on 06 September 2008, 6-hour ensemble forecasts are made from the ensemble analyses and used to compute the background error covariance for the next assimilation/analysis time. The initial and boundary ensemble mean conditions are obtained from the 1°×1° degree global aviation (AVN) analysis produced by NOAA's National Centers for Environmental Prediction (NCEP). The initial and boundary ensembles are generated by adding random draws from a distribution with the forecast error covariance statistics of the WRF 3D-Var data assimilation system to the mean fields. Following the assimilation period, a set of 96 hours forecasts initialized from the ensemble analyses on 00 UTC 08 September 2004 are performed and evaluated.

[9] The WRF model is configured with a 36-km horizontal resolution with 35 vertical levels from the surface to 50 hPa (~20 km). The analysis domain covers the tropical Atlantic Ocean (0°N–40°N, 30°W–110°W). Thirty-six ensemble members are used in the assimilation experiments. AIRS SFOV clear sky soundings from 20 granules on 06 and 07 September 2008 (5°N–25°N, 30°W–85°W) are generated using the CHISR algorithm. Figure 1 shows the clear sky AIRS SFOV water vapor mixing ratio retrievals at 700 hPa on 06 September 2008 overlaying the 11 μm brightness temperature (black/white) image; each pixel in color provides vertical temperature and moisture soundings in clear skies.

[10] NCAR WRF/DART ensemble assimilation system for 00 UTC 06–08 September 2008 is used, and an analysis

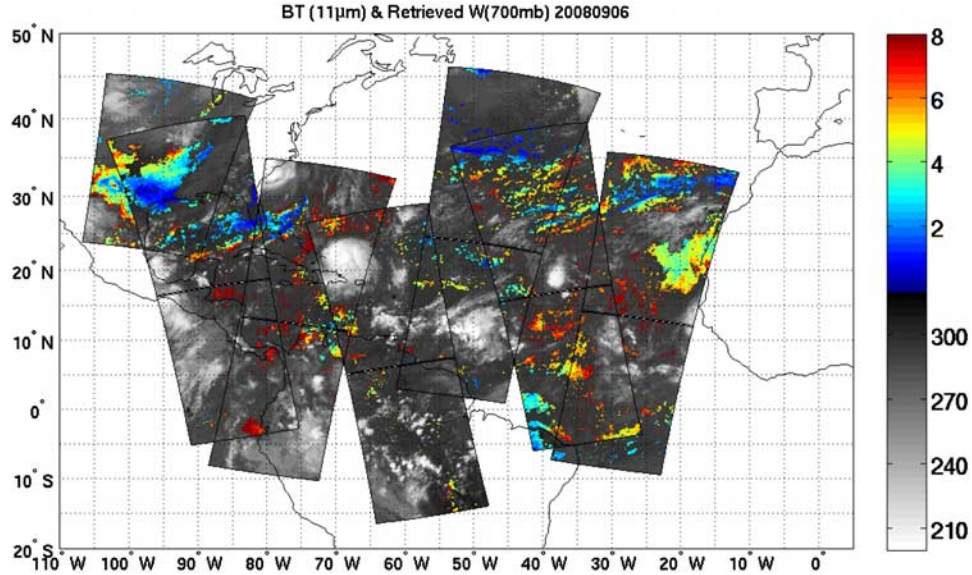

Figure 1. The clear sky AIRS SFOV water vapor mixing ratio (g/kg) retrievals at 700 hPa on 06 August 2008 overlaying a 11 μm brightness temperatures (K) (back/white) image. Each color pixel represents an atmospheric sounding (temperature and moisture profiles).

is generated every 6 hours. The CTRL run already assimilates radiosonde, satellite visible and imager water vapor cloud winds, aircraft data, QuikScat surface winds, and hurricane position data. The assimilation run (natural run) is carried out in the following three configurations: (1) by including the AIRS SFOV temperature and moisture profiles (13.5 km at nadir) with the CHISR algorithm; (2) by including operational AMSU temperature profiles ($\sim$50 km at nadir); (3) by including both the AIRS SFOV soundings with CHISR and the operational AMSU temperature profiles.

[11] Figure 2 (top) shows the Hurricane Ike track analysis from the control run (blue line), the assimilation of AIRS SFOV clear sky soundings with the CHISR algorithm (blue line), the operational AMSU temperature profiles (green line), both AIRS and AMSU profiles (magenta lines), along with the hurricane track observation (red line). Figure 2 (middle) shows the track error (km) in the analysis period, starting from 06 UTC on 06 September 2008, from the control run (black line), the natural run with AIRS clear sky soundings (blue line), the natural run with AMSU temperature profiles (green line), and the natural run with both AIRS and AMSU profiles included (magenta line). From Figure 2, it can be seen that after 12 hours in the assimilation period, the track error was cut in half when AIRS clear sky SFOV soundings are included. AMSU temperature profiles also reduce track errors but not substantially; this might be partially due to the lack of moisture information (with the failure of HSB) in this particular case. Inclusion of both AIRS and AMSU profiles provides results similar to using AIRS only. The sea level pressure (SLP) in Figure 2 (bottom) also shows the improvement of about 10 $\sim$ 20 hPa after 24 hours when AIRS SFOV soundings are assimilated. The improvement is due to the key temperature and moisture observations at high spatial resolution in the storm environmental regions. The AMSU temperature profiles do not provide substantial help for the SLP forecast in this particular case.

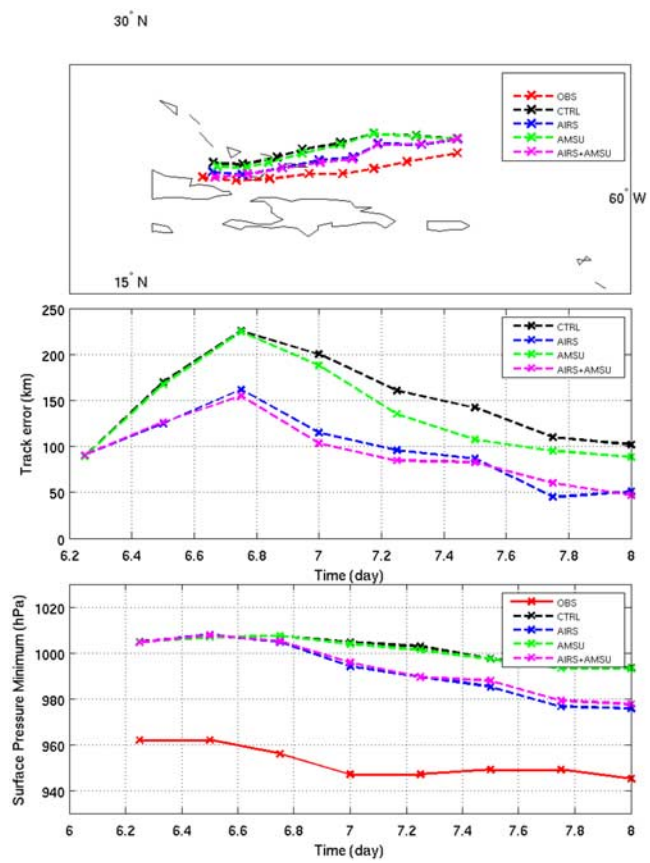

Figure 2. The 48-hour analysis of Hurricane Ike for (top) the hurricane tracks, (middle) the track errors in km and (bottom) the central sea level pressures from different data: the control run (black line), assimilation of AIRS SFOV soundings (blue line), the assimilation of AMSU temperature profiles (green line), the assimilation of both AIRS and AMSU profiles (magenta line), along with the observation (red line). The starting time is 00 UTC on 06 September 2008.

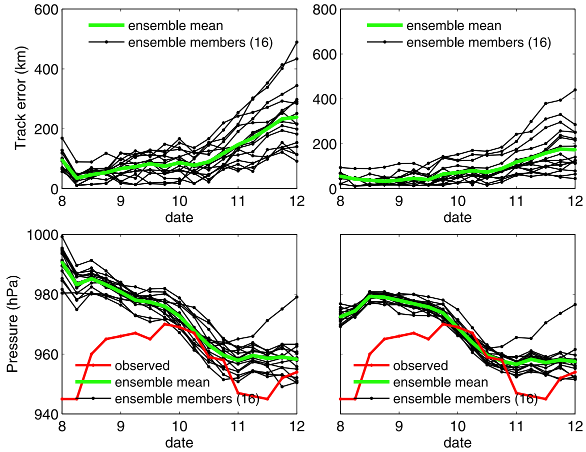

Figure 3. (top) The 96-hour track error and (bottom) central sea level pressure forecasts of hurricane Ike initialized from the analysis at 00 UTC 08 September 2008. (left) Control runs and (right) the results with initials assimilated from CIMSS AIRS SFOV sounding retrievals. The black lines represent the results from each ensemble member forecast and the green lines are the ensemble mean; the red lines are the observation.

[12] The track errors and SLPs in the 96-hour forecasts for the control and AIRS run are shown in Figure 3 for each of the first 16 ensemble members and the mean of the ensemble tracks and SLPs. The forecast track errors increase in the 96-hour forecast period due to the model error accumulation and no more new information added. The ensemble mean of track errors from assimilating CIMSS AIRS SFOV sounding data, however, are consistently lower than that of the control run in the entire forecast period, with about 174 km and 239 km errors, respectively, at 00 UTC on 12 September 2004. With high spatial resolution temperature and moisture information in AIRS SFOV retrievals, SLP forecast is better and closer to the observation; especially the up-down structure in the observation is well captured. The variability among the ensemble members is also much less with AIRS SFOV sounding data than that of the control run.

6. Summary

[13] This study demonstrated the potential applications of high spatial and vertical resolution soundings retrieved from advanced IR sounder radiance measurements in the hurricane track and intensity forecast. The AIRS SFOV soundings ($\sim$13.5 km spatial resolution at nadir) show positive impact on a hurricane (Ike) track both in assimilation and forecast using the WRF/DART system with 36 km spatial resolution. The advanced IR sounder provides much better impact than the AMSU temperature profiles with lower spatial resolution ($\sim$50 km at nadir). More hurricane cases will be studied using data from advanced IR sounders such as AIRS, and IASI, as well as microwave sounding data such as AMSU-A and AMSU-B. Experiments will also be extended to include cloudy soundings retrieved from IR radiance measurements.

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