Improving Regional Forecast by Assimilating Atmospheric InfraRed Sounder (AIRS) Profiles into WRF model

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1. INTRODUCTION

The use of state-of-the-art hyperspectral sensors—such as the Atmospheric InfraRed Sounder (AIRS) on NASA’s polar-orbiting Aqua satellite—to retrieve high vertical resolution thermodynamic profiles and their subsequent assimilation into forecast models holds promise in improving weather predictions. This improved vertical resolution over previous capabilities results from the use of thousands of channels in the retrieval process instead of 10-20 channels for previous instruments. Although these capabilities do not replace the robust vertical resolution provided by radiosondes, these retrieved soundings can have a significant impact on weather forecasts if properly assimilated into prediction models.

Several recent studies have evaluated the performance of specific operational weather forecast models when AIRS data are included in the assimilation process. LeMarshall et al. (2006) concluded that the AIRS radiances significantly improved 500 hPa anomaly correlations in medium-range forecasts of the Global Forecast System (GFS) model at the Joint Center for Satellite Data Assimilation. McCarty et al. (2009) demonstrated similar forecast improvement in 0-48h forecasts in an off-line version of the operational NAM run by NCEP through the use of AIRS radiances at the regional scale. Reale et al. (2008) showed improvements to Northern Hemisphere 500 hPa height anomalies in NASA’s GEOS-5 global system with the inclusion of partly cloudy AIRS temperature profiles. Singh et al. (2008) assimilated AIRS temperature and moisture profiles into a regional modeling system for a study of a heavy rainfall event during the summer monsoon season in Mumbai, India.

This paper describes an approach to assimilate AIRS temperature and moisture profile data into a regional configuration of the Weather Research and Forecasting (WRF) model (Skamarock et al. 2005) using its three-dimensional variational (3DVAR) assimilation component (WRF-Var; Barker et al, 2004) for a 37-day case study period in the winter of 2007. Unique to this approach is the use of AIRS profiles in both clear and cloudy regions, partial profiles above low-level clouds, and the use of varying error weights for land and oceanic retrievals in the assimilation scheme.

2. AIRS PROFILES

The AIRS and the Advanced Microwave Sounding Unit (AMSU), on the EOS polar-orbiting Aqua satellite with an early afternoon equatorial crossing time, form an integrated temperature and humidity sounding system for numerical weather prediction and climate studies. Due to its hyperspectral nature, AIRS can provide near-radiosonde-quality atmospheric temperature and moisture profiles with the ability to resolve some small-scale vertical features. The superior vertical resolution and sounding accuracy make the instrument very appealing as a complement to radiosonde measurements in data sparse regions.

Standard Version 5 temperature and moisture soundings, which contain 14 vertical levels between 1000 and 50 hPa, are used to mitigate some of the effects of vertical correlation inherent to profiles retrieved from satellites. Globally, the AIRS Version 4 retrieved profiles (produced with an early version of the AIRS science team retrieval algorithm)—compared to radiosondes collocated in time and space—exhibit RMS errors of 1 K in 1-km layers for temperature and 15% RH in 2-km layers for water vapor, which both fall at or below the pre-launch expectations of the instrument. The smallest retrieval errors occur for clear-sky cases over water with degradation in profile accuracy in cloudy and/or overland scenes (Tobin et al. 2006; Divakarla et al. 2006). Although, no formal validation of the Version 5
products has been published, the retrieval errors are smaller than those of the Version 4 data as modifications to improve the quality of the soundings occurred in the later version (Susskind, personal communication).

Quality indicators (QIs) that are part of the Level-II products are used to ensure that only the highest-quality data from each profile was assimilated in the forecast model. In the retrieval process, a profile is generated from the top of the atmosphere down, and there is a specific level below which data are of questionable quality (due to higher than expected retrieval uncertainties). This level is generally consistent with cloud tops and/or failures in cloud clearing but can also be attributed to inappropriate surface emissivity specifications for channels which sense surface emission over land. Thus, each profile contains a variable, \( P_{\text{best}} \), which defines a specific level below which data are of questionable quality. Intelligent interpretation of the QIs enables assimilation of only the highest quality data and should help yield improved forecasts in the 0- to 48h time frame.

In this study, the \( P_{\text{best}} \) is used to select the optimal data from each profile for assimilation. A three-dimensional distribution of AIRS profile locations and \( P_{\text{best}} \) for 17 January 2007 is shown in Figure 1. The location of each AIRS profile is represented as a colored box with each color representing its \( P_{\text{best}} \) pressure level. In the figure, the black squares represent soundings that are of the highest quality at all levels, and each of the colored squares represents the pressure level above which observations are assimilated. White regions are data gaps between successive AIRS orbital swaths or missing profiles due to a failure of the retrieval algorithm due to dense overcast conditions. It should be noted that most of the highest quality (black) soundings are located over the ocean.

Poorly-defined infrared emissivity in channels sensitive to surface emission, resulting from inhomogeneous or unknown land types can lead to degraded AIRS retrievals in over land soundings (Borbas 2007). Thus, over land retrievals generally have larger errors than those over water. In this study, both land and water soundings are assimilated and treated as two separate observation types in the analysis process. To accomplish this task, the WRF-Var source code was altered to accommodate AIRS-land and AIRS-water data sets with separate observation errors. Figure 2 shows the observational errors for land (dotted line) and water (dashed line) soundings (solid line denotes background error; see section 3) used in this study.

![Fig. 1. Quality indicators for AIRS profiles assimilated at 0800 UTC on 17 January 2007. The black points represent the highest quality data, and each colored point denotes the pressure level above which there are quality data. The red rectangle denotes the bounds of the WRF model domain.](image)

![Fig. 2. Background (black) errors and observation (blue: AIRS-water, green: AIRS-land) errors for WRF-Var analysis for temperature (left) and relative humidity (right).](image)

### 3. MODEL DESCRIPTION AND EXPERIMENTAL DESIGN

The forecast model used herein is the Advanced Research WRF (ARW), which is a subset of the WRF modeling system and designed specifically for research purposes. The WRF model consists of multiple options for various physical parameterization schemes. The major physical options used for this study are summarized in Table 1.

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The WRF-Var is the 3DVAR data assimilation component of WRF (Barker et al., 2004), which works by minimizing a cost function to estimate the true state of the atmosphere using a previous forecast (background), observations, and their respective errors. At each grid point, these errors define the weighting of the background and observations such that larger background error for a given variable will result in an analysis more closely resembling the observation (and vice versa).

A background error covariance matrix specific to the domain and season used in this study was created using the “gen_be” program in the WRF-Var package. This program uses the National Meteorological Center (NMC) method (Parrish and Derber, 1992), which assumes that the background error covariances are well approximated by averaged forecast differences between 24-h and 12-h forecasts verified at the same time. The resulting background values used over the entire domain are shown in Figure 2. Note that the errors change as a function of pressure with different profiles used over the water and land regions.

For this study, ARW Version 2.1.1 is used. The model domain consists of a 450 x 360 grid with 12-km spacing that covers the contiguous United States, Western Atlantic Ocean, and Gulf of Mexico (see red box in Fig. 1). It has 37 staggered terrain-following vertical levels with the top-level pressure at 50 hPa and finest resolution near the lower boundary.

Two identical WRF configurations are run in parallel with one assimilating AIRS profiles (AIRS) and one without (CNTL). The test case period covers 17 January to 22 February 2007 and consists of 37 48-hour forecasts. Each WRF forecast is a cold start initialized with a 0000 UTC North American Mesoscale (NAM) analysis. The boundary conditions are updated every 3 hours using the NAM forecasts. A short-term WRF forecast is run from the initialization time to the time of the observations and is used as the first-guess field for the WRF-Var analysis. The analysis time is determined by the mean of the two morning (AM) AIRS data swaths over central and eastern North America rounded to the nearest hour. The observation time for the AM overpass varies between 0700 and 0900 UTC due to the daily orbital progression of the Aqua satellite. AIRS profiles from the afternoon overpasses are not assimilated. The WRF-Var analysis re-initializes the WRF for the AIRS runs and produces a 48-h forecast. The CNTL forecasts were run in the same manner except that no AIRS profiles were assimilated. No other observations or profiles are assimilated in this experiment.

4. ANALYSIS IMPACT

The analysis impact of AIRS on 700 hPa temperature and mixing ratio for 17 January 2007 is shown in Figure 3. Figures 3a and 3b show the innovations of the AIRS temperature and mixing ratio using an 8-h WRF forecast as the background. AIRS temperatures are warmer than the background across the southeast U.S. but are cooler across south Florida and the Great Lakes. The AIRS observations are at times 4°C warmer or cooler than the background. AIRS moisture is generally moister than the background, except in the region from the Florida panhandle to coastal South Carolina. The moisture innovations are generally constrained to ±2 g/kg except over north Georgia.

Figures 3c and 3d show the temperature and mixing ratio analysis increments (analysis minus background) for the AIRS analyses. The analysis increments depict a similar pattern to the innovations in Figures 3a and 3b. As expected, the analysis lies between the background and observations with temperature analysis increments of ±2.5°C, which are smaller than their innovation counterparts in Figure 5a. The moisture fields at 700 hPa also show a similar impact with analysis increments in the ±1 g/kg range. Patterns in the 700 hPa results are representative of results at other levels.

To further illustrate the impact of the AIRS profiles on the analysis, Figure 6 shows a comparison between a series of sounding profiles collocated near the Wallops Island, VA (WAL; marked “x” in Fig. 5a) radiosonde site on 17 January 2007. The background (black) and analysis (red) profiles are chosen at the closest analysis grid point to WAL; the radiosonde profile (green) is a linear interpolation of the 0000 and 1200 UTC radiosondes to the analysis time (0800 UTC). The closest AIRS observation to the analysis grid point is shown in blue. The background value at this location is too cool and dry above 700 hPa compared to the anticipated conditions defined by the time-interpolated radiosonde. The AIRS observation (data below 700 mb has been removed by the QC procedures) is warmer and moister than the background above 700 hPa. While the AIRS...
The AIRS profile (blue) is for the highest-background or AIRS observation. The resulting moisture analysis is closer to the profile appears slightly too moist. However, the atmosphere above 700 hPa, the AIRS moisture representation of the true state of the profile temperature appears to be a better background indicating probable conditions at the analysis time than the analysis with AIRS profiles better represent the radiosondes plotted to show that the AIRS profile and linearly-

Fig. 3. Analysis impact of AIRS at 700 hPa for 0800 UTC 17 January 2007. The top row shows innovation fields (AIRS-background) for a) temperature (°C) and b) mixing ratio (g/kg). The corresponding analysis increments (WRF-Var minus background) are shown in c) and d). The “x” in a) denotes the location of the Wallops Island, VA (WAL) sounding detailed discussed in the text.

Fig. 4. Temperature (solid) and dew point (dashed) profiles near Wallops Island, VA (WAL) for 0800 UTC 17 January 2007. The background (black) and WRF-Var (red) profiles are for the nearest grid point. The AIRS profile (blue) is for the highest-quality retrieval closest to the grid point. The WAL radiosonde is a linearly-interpolated sounding of the 0000 and 1200 radiosondes plotted to show that the AIRS profile and analysis with AIRS profiles better represent the probable conditions at the analysis time than the background indicating analysis improvement.

profile temperature appears to be a better representation of the true state of the atmosphere above 700 hPa, the AIRS moisture profile appears slightly too moist. However, the resulting moisture analysis is closer to the presumed true atmospheric state than either the background or AIRS observation. The assimilation procedure leads to a warmer analysis that is closer to the presumed true atmospheric state than the original background data.

5. FORECAST IMPACTS

An evaluation of the impact of the assimilation of AIRS profiles on WRF forecasts was conducted by performing a statistical comparison of sensible weather parameters for the AIRS and CNTL runs. Temperature, mixing ratio, and geopotential height in these forecasts were compared to the 40-km NAM analyses for all corresponding grid regions east of 105°W every 6 hours for the daily 48-h forecasts for the 37-day case study period (17 January to 22 February 2007). For precipitation, forecast accuracy was evaluated by comparing the model outputs to 4-km NCEP Stage IV precipitation data. For consistency with the NAM comparison, only coincident grid regions that lie to the east of 105°W longitude are used for the precipitation verification. The 105°W longitudinal demarcation is selected as it represents regional where we expect AIRS to have an impact based on the data assimilation region.

5.1. WRF forecast evaluation with the NAM

The AIRS and control run statistics were calculated every 6 hours from 12 h to 48 h to examine AIRS impact on the WRF forecasts. Figure 5 shows the cumulative statistics for the bias and root mean square error (RMSE) of temperature, mixing ratio, and geopotential height averaged over all 37 case study days and all verification hours (CNTL runs are dashed lines; AIRS runs are solid lines). The biases in Figure 5 represent the forecast minus analysis such that negative biases indicate that AIRS and CNTL forecasts have cooler temperatures, drier mixing ratios, and lower heights than the analysis; positive biases indicate that AIRS and CNTL forecasts have warmer temperatures, moister mixing ratios, and higher heights. For temperature (Figs. 5a and 5b), the CNTL run is cooler in the lower and middle troposphere and warmer in the upper troposphere compared to the NAM analyses. With the addition of AIRS profiles, most levels show a reduction in the CNTL run bias with AIRS warming the cool-biased lower and middle troposphere and cooling the warm-biased upper troposphere by as much as 0.2°C in the boundary layer. The
inclusion of AIRS shows a slight increase in RMSE (≤ 0.1°C) throughout the troposphere over the CNTL.

For mixing ratio (Figs. 5c and 5d) the CNTL run is too dry below 700 hPa, but is within 0.1 g/kg of the NAM analyses in the middle and upper troposphere. Overall, the AIRS profiles have a moistening effect (with respect to the CNTL) throughout most of the atmosphere. While there is very little change between the CNTL and AIRS runs in the boundary layer, the AIRS runs add moisture to the forecasts above the boundary layer. Between 900 and 700 hPa, the added moisture results in improved forecasts of mixing ratio bias; however, above 700 hPa, the added moisture results in degraded forecasts. As with temperature, the mixing ratio RMSE is slightly increased (< 0.1 g/kg) with the addition of AIRS.

For geopotential height (Figs. 5e and 5f), the CNTL runs are biased towards lower heights compared to the NAM analyses, except at the surface. The overall trend associated with the inclusion of the AIRS profiles is to raise the heights. There appears to be a systematic increase of between 5 and 8 meters at all levels leading to improved bias at most levels (the exceptions being the surface and 850 hPa). For this case study period, the systematic raising of the heights results in positive forecast improvement. Further investigation reveals that AIRS tends to have a warmer temperature than the background at 1000 hPa, which leads to an overall increase of geopotential height throughout the atmosphere over the ocean. The results of this warming can be seen by the warm bias exhibited in Fig. 5a whereby the near-surface AIRS temperature bias is increased compared to the CNTL. Improved temperature bias in the near-surface AIRS forecasts may indicate that the systematic bias in the AIRS geopotential heights in the mid-troposphere are indeed improved over the CNTL.

**5.2 Cumulative Precipitation Evaluation**

An evaluation of the accuracy of precipitation forecasts is made by comparing the model output precipitation from the AIRS and CNTL forecasts with 4-km NCEP Stage IV radar 6-h composite data mapped to the WRF model domain. Precipitation fields are compared using bias scores and equitable threat scores (ETS) (Hamill 1999) based on the statistics of precipitation amount exceeding various numerical thresholds. The bias score is a ratio of the number of observed points to the number of forecasted points that exceed the threshold value and is a measure of how accurate the forecast predicts the precipitation coverage. A bias score of 1.00 denotes perfect agreement in
precipitation coverage between forecast and observations. Bias scores greater than 1.00 denote over forecasting; less than 1.00 denote under forecasting. The ETS indicates how well the forecasted rainfall region matches the observed rainfall region that exceeds a given threshold. Higher ETS indicates more accurate forecasts of precipitation location and intensity. An ETS of 1.00 indicates that the precipitation fields are perfectly aligned, and an ETS of 0.00 means that there are no matches at all. The ETS is a good indicator of whether forecasts are improved over persistence or random correct guesses.

The 6-h precipitation was calculated every 6 hours starting at 12 UTC. The precipitation comparisons were made by averaging over the whole 37-day case study period and covering all the forecast hours where there are verifying observations (Fig. 6). For the bias score (lines in Fig. 6), the CNTL over-forecasts the area coverage of the lower thresholds but under-forecasts that of the higher thresholds. With AIRS assimilated, coverage of the light rain is reduced but coverage of the heavy rain increases, therefore, statistically improving the forecast of the area precipitation coverage. The improvement is also shown in the forecast of precipitation location. The ETS (bars in Fig. 6) for each precipitation threshold is increased with the assimilation of AIRS profile data with the exception of the heaviest rain cases (> 50.8 mm/6h). Overall the combination of the ETS and bias results indicate that addition of the AIRS profiles has a positive impact on precipitation forecasts.

6. SUMMARY AND CONCLUSION

A methodology for assimilating Version 5 Level-II AIRS thermodynamic profiles into the WRF using the 3DVAR analysis component (WRF-Var) has been developed and applied to a winter case study of 37 days from 2007 over the eastern two-thirds of the U.S. The 0000 UTC NMC NAM analysis was used to initialize the WRF model which was then run to averaged AIRS overpass time (between 0700 and 0900 UTC) for AIRS data assimilation. Quality indicators developed by the AIRS science team were use to identify only the highest quality AIRS data, which are assimilated as separate land and water soundings. Results indicate that AIRS profiles produced an analysis closer to in situ observations than the background field. Forecast results indicate that temperature and mixing ratio fields were improved in the lower troposphere but slight degradations occurred in the mid- and upper-troposphere when compared to NAM analyses. The geopotential height showed an overall increase in bias at all levels with the inclusion of AIRS leading to degradation in the lower troposphere but improvements in the mid- and upper-troposphere when compared to the NAM. The 6-h cumulative precipitation forecasts verified against NCEP Stage IV precipitation data show improvement in both the location and coverage of precipitation when AIRS profiles are assimilated.

REFERENCES

