The Impact of Near-Real-Time AIRS Thermodynamic Profiles on Regional Weather Forecasting

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Abstract

One of the mission goals for the Atmospheric InfraRed Sounder (AIRS) is to provide sounding information of sufficient accuracy such that the assimilation of the new observations—especially in data sparse regions—yields improvement in weather forecasts. Coupled with the Advanced Microwave Sounding Unit (AMSU), AIRS provides radiance measurements used to retrieve temperature profiles with an accuracy of 1 K over 1 km layers and moisture profiles with an accuracy of 15% in 2 km layers under both clear and partly cloudy conditions. Explicit use of level-by-level error estimates allows for the use of the highest quality AIRS profiles in the assimilation process to provide improved initial condition for numerical weather prediction.

The purpose of this paper is to describe a methodology to selectively assimilate AIRS temperature and moisture data into a regional analysis/forecast model. The paper will focus on the overall impact of AIRS profiles on forecast accuracy for an extended period from the winter/spring of 2007. Using the ARPS Data Analysis System (ADAS), temperature and moisture profiles from the Version 5.0 EOS science team retrieval algorithm were used to update a background field from the NCEP North American Mesoscale (NAM) Model. The AIRS-enhanced analyses were used as initial fields for the Weather Research and Forecasting (WRF) Model for short-term (0-48 hr) regional forecasts. The analysis/forecast system was run in a near-real-time environment on a Continental United States domain. Results will focus on forecast impact from AIRS on sensible parameters (e.g. temperature, moisture, winds, and cumulative precipitation) from the near-real-time forecasts.

INTRODUCTION

Significant weather events can often occur in regions downstream of sparse data (e.g. coastlines, deserts, large forests, etc.). Without adequate observations, meteorological analyses revert to the background (i.e. first guess) field, typically consisting of a previous gridded forecast. Observations from satellites are one valuable option to complement traditional atmospheric observations in these data sparse regions. Currently, the most state-of-the-art NASA atmospheric profiler is the Atmospheric InfraRed Sounder (AIRS). AIRS radiances have been assimilated into global models yielding improvements in 5-day forecasts (e.g. Le Marshall et al. 2006, Garand et al. 2006, Jung et al. 2006). However, for centers focusing on regional forecasting problems—such as the SPoRT Center (Goodman et al. 2004)—impact of AIRS profiles on thermodynamic structures is a logical first step to using AIRS data. A methodology for assimilating AIRS profiles is presented herein.

Previous work (e.g. Chou et al. 2007) has focused on a single case study. This paper extends the methodology from that single case study to an extended period of observation to develop a set of long-term statistics to assess forecast impact from AIRS. First, a description of the AIRS data used for this study is given. Next, a brief overview of the analysis and forecast strategy used to produce the simulations is presented followed by the experiment design. Then, the forecast impacts of the AIRS data on temperature, mixing ratio, and precipitation forecasts are provided. Finally, conclusions and future work are offered.

AIRS DATA

AIRS Specifications

Aboard the EOS polar-orbiting Aqua satellite with an early afternoon equatorial crossing time, AIRS coupled with the Advanced Microwave Sounding Unit (AMSU) form an integrated temperature and humidity sounding system. AIRS is a cross-track scanning infrared spectrometer/radiometer with 2378 spectral channels between 3.7 and 15.4 μm (650 and 2675 cm^{-1}). Due to its hyperspectral nature, AIRS can provide near-rawinsonde-quality atmospheric temperature profiles with the ability to resolve some small-scale vertical features. AIRS footprints coincide with AMSU footprints allowing AMSU data to be used in the retrieval process. This produces a uniform distribution of AIRS retrievals in both clear and partly cloudy scenes at a spatial resolution of approximately 50 km (Aumann et al. 2003). The superior vertical resolution and sounding accuracy make the instrument very appealing as a complement to rawinsonde measurements in data sparse regions.

Version 5 AIRS temperature and moisture profiles over both land and water are used for this study. Each sounding contains approximately 54 vertical levels between 1013.25 and 100 hPa. Globally, the AIRS version 4.0 retrieved profiles—compared to rawinsondes collocated in time and space—exhibit RMS errors of 1 K in 1-km layers for temperature and 10-15% RH in 2-km layers for moisture (Tobin et al. 2006, Divakarla et al. 2006). The lowest errors occur for clear-sky cases over water with degradation in profile accuracy in cloudy and/or over-land fields of view (FOVs). Although Version 5 profiles have not yet been fully validated, improvements to the radiative transfer algorithm and quality indicators should lead to improved profile accuracy (Susskind, personal communication).

Quality Indicators in Version 5.0 AIRS Data

Each profile contains level-specific quality indicators allowing users to determine which parts of a profile are best for their applications. Because each retrieved profile is generated from the top of the atmosphere down, there is a specific level below which data is of questionable quality. This level is generally consistent with cloud tops and/or failures in cloud clearing but can also be attributed to faulty emissivity measurements over land. As an example, for low-level clouds, the upper two-thirds of a profile may be valid; however, for thick convective clouds, an entire profile may be deemed questionable.

In this study, the quality indicators are used to select which levels of an AIRS sounding are to be assimilated into the analysis/forecast system. A plot of the three-dimensional distribution of AIRS profiles assimilated for this case study is shown in Figure 1. In the figure, temperature and moisture data above the indicated pressure level are used. The reader should refer to Susskind (2007) for a more detailed explanation of how the quality indicators are generated. Optimal use of these quality indicators will enable assimilation of only the highest quality data and is expected to yield improved forecasts in the 0- to 48-h time frame.

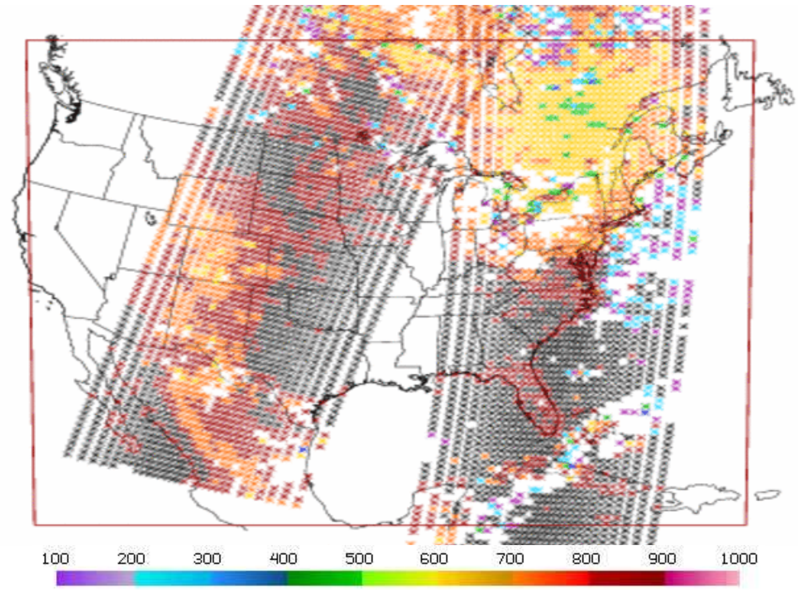

Figure 1: **Three-dimensional distribution of AIRS profile data assimilated at 0800 UTC 26 January 2007 (right swath valid at 0700-0712 UTC, left swath valid at 0836-0848 UTC). Each point denotes the maximum pressure level corresponding to the level above which data is of good quality. The black points represent the highest quality data; white space indicates no sounding. The rectangle denotes the bounds of the WRF/ADAS domain.**

ANALYSIS AND FORECAST SCHEMES

ARPS Data Analysis System (ADAS)

The Advanced Regional Prediction System (ARPS; Xue 2001) Data Analysis System (ADAS; Brewster 1996) provides a means to merge different sources of meteorological data into a coherent three-dimensional description of the atmosphere and has been configured to assimilate satellite profiles from AIRS. In this study, only AIRS data are used to produce the analyses. No other data sets (e.g. rawinsondes, surface observations, aircraft observations, etc.) are assimilated. Error covariances used for the background are standard short-term forecast errors cited in the ADAS documentation, and the error tables used for the AIRS profiles (different errors for over-land and over-water soundings) are based on estimates cited by Tobin et al. (2006) for Tropical Western Pacific (TWP) and Southern Great Plains (SGP) validation experiments of version 4.0 profiles. For more information on the ADAS configuration used in this project, the reader is referred to Chou et al. (2006) and Chou et al. (2007) and Jedlovec et al. (2006).

Weather Research and Forecasting (WRF) Model

The forecast model used herein is the Weather Research and Forecasting (WRF; Skamarock 2005) model, a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. It is a limited-area, non-hydrostatic primitive equation model with multiple physical parameterization options. The model domain consists of a 450 x 360 grid with 12-km spacing and covers the contiguous United States, Western Atlantic Ocean, and Gulf of Mexico (see Fig. 1). It has 37 staggered terrain-following vertical levels with the top-level pressure at 100 hPa and finest resolution near the boundary layer. The WRF physical options used in this project are described in more detail in Chou et al. (2007).

EXPERIMENTAL DESIGN

The WRF is initialized with the 40-km North American Mesoscale (NAM) model analyses, which are available every 6 hours. The boundary conditions are updated every 3 hours using the NAM forecasts. Although the NAM is available at 0600 UTC, using an earlier initialization allows the model to adjust dynamically prior to data assimilation. The NAM forecast is then used as the first guess field for the ADAS analysis when the AIRS profiles in the forecast domain are valid. An eastern and central swath are combined (as in Fig. 1) and assimilated simultaneously to avoid frequent starting and stopping of the modeling system. Simulations are performed for 33 days between 17 January 2007 and 22 February 2007 (3-5 February 2007 and 11 February 2007 were omitted because of missing NAM initial conditions).

Although not available at the time of this publication, the plans for this modeling system include using AIRS version 5.0 support files obtained in near-real-time from the University of Wisconsin Direct Broadcast. For the work contained herein, profiles were obtained from the Goddard Earth Sciences Data and Information Services Center (GES DISC) and not assimilated in near-real-time. Decisions are made depending on the location of the Aqua overpass regarding which granules will be used. Data from the western-most overpass of Aqua are omitted, as short-term forecast impact from these granules will not be apparent in the southeastern United States. The ADAS analysis initializes the WRF for the AIRS-assimilated runs and produces a 48-hr forecast. The control run is performed in the same manner except no data are assimilated within the ADAS. The forecast/analysis cycle for the experiment is highlighted in Figure 2.

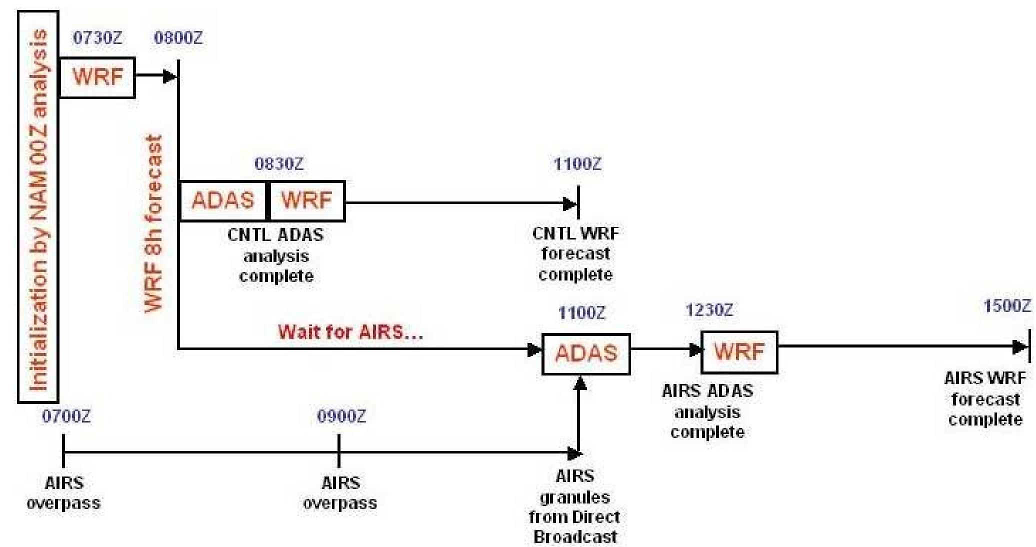

***Figure 2*: Example of the configuration of experiments for near-real-time ADAS/WRF coupling. Wall time of each process is denoted in blue text.**

FORECAST IMPACT

Temperature and Moisture Statistics

The purpose of this experiment is to show impact of the AIRS data on sensible parameters in the WRF forecasts by comparing parallel runs of the WRF: one with AIRS (AIRS) and one without (CNTL). Comparisons were made to 50 east-coast rawinsondes east of 105°W (Fig. 3) every 12 hours. Statistics were compiled for 0 to 48-hr forecasts from January 17 through February 22, 2007 (with the omission of the days cited in the previous section).

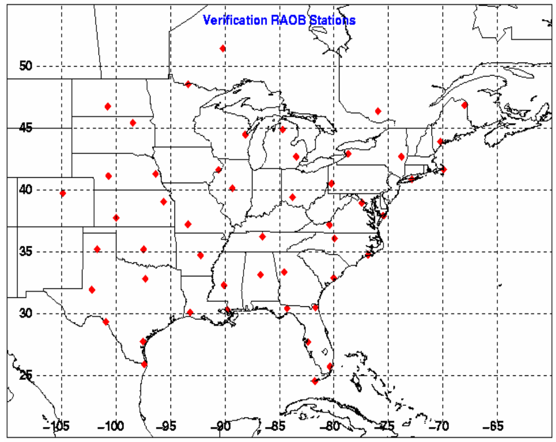

***Figure 3*: Location of rawinsonde observations (east of 105°W) used to generate month-long comparison statistics.**

Figure 4 shows the cumulative statistics for the bias and root mean square error (RMSE) for temperature and mixing ratio for the 36-hr forecasts. The mixing ratio statistics are shown as relative values normalized with the average observed value. Differences shown in Fig. 4 are forecast minus observation such that biases less than zero indicate forecasts that are cooler and drier than the observations; biases greater than zero indicate forecasts that are warmer and moister.

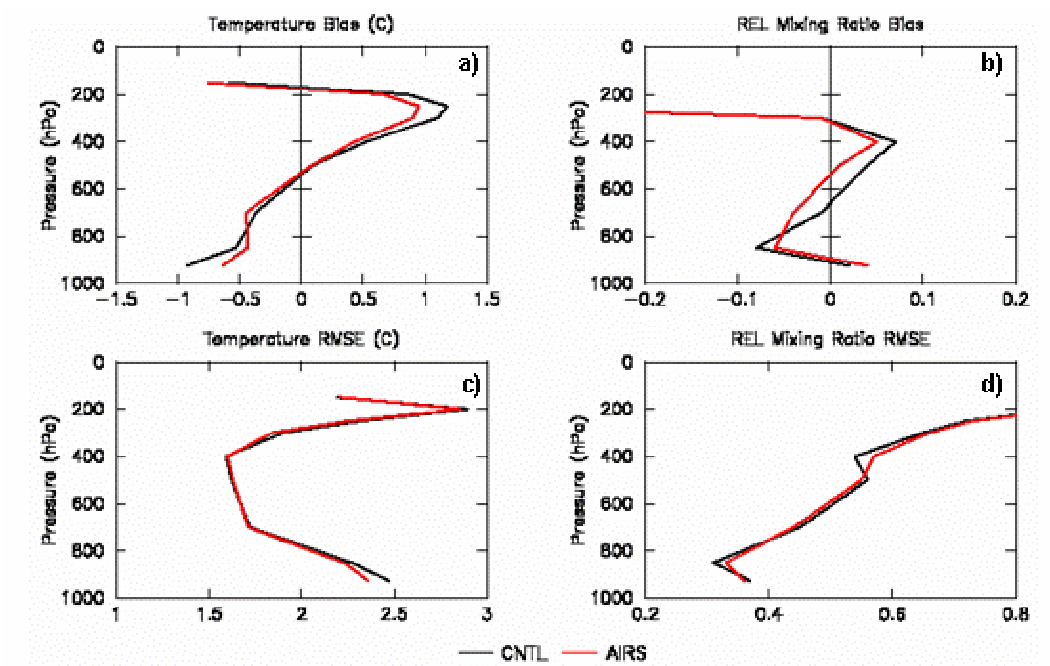

***Figure 4*: Statistics of 36-h forecast temperature (°C) a) bias (forecast – rawinsonde) and c) root mean square error (RMSE) and dew point temperature (°C) b) bias (forecast – rawinsonde) and d) RMSE for 33 days between January 17 and February 22, 2007. The black line represents the CNTL case; the red line represents the AIRS case.**

For temperature, the control run is cool biased in the lower and upper troposphere and warm biased in the middle troposphere. Most levels show a reduction in bias with the AIRS runs warming the cool-biased lower and upper troposphere and cooling the warm-biased middle troposphere. All of these changes are made without an increase in the RMSE, which is a measure of the variance of the forecast differences. The only noticeable difference in the RMSE between the AIRS and the CNTL is at the lowest validation level. The lack of an RMS error increase further validates that the improvements to the overall bias statistics are moving the forecasts closer to the value of the rawinsondes rather than creating larger positive and corresponding negative biases to move the overall bias closer to zero.

Mixing ratio statistics yield similar results. The lower and upper troposphere in the CNTL is too dry, and the middle troposphere is too moist. AIRS increases moisture to the lower troposphere and reduces middle-tropospheric moisture. There is a slight degradation of the forecast between 750 and 600 hPa, but there is also a large improvement of upwards of 5% of the atmospheric moisture content at the levels between 600 and 400 hPa. As with the temperature results, the mixing ratio results are accompanied by no large increases to the RMSE.

The results for both temperature and mixing ratio are representative of most forecast times in that AIRS reduces the bias at most levels without a significant increase to RMSE.

Precipitation Statistics

Verification of precipitation forecasts are made by comparing the model output precipitation fields with 4-km NCEP Stage IV radar 6-h composite data. For consistency with the rawinsonde verification, the Stage-IV data are mapped to the WRF model domain for direct comparison, and verification statistics are calculated for grid points that lie to the east of 105°W longitude. Precipitation is verified using bias scores and equitable threat scores (ETS) (Gandin and Murphy 1992) based on the amount of precipitation larger than 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 indicates perfect precipitation coverage while a value less (more) than 1 indicates under (over) forecasting of precipitation over the grid. The ETS incorporates forecast hits and misses to measure how well the model forecasts the rainfall location. It gives a quality score between 0 and 1 with an ETS of 1 indicating perfect alignment of observed and forecasted precipitation and an ETS of 0 meaning there are no matches at all.

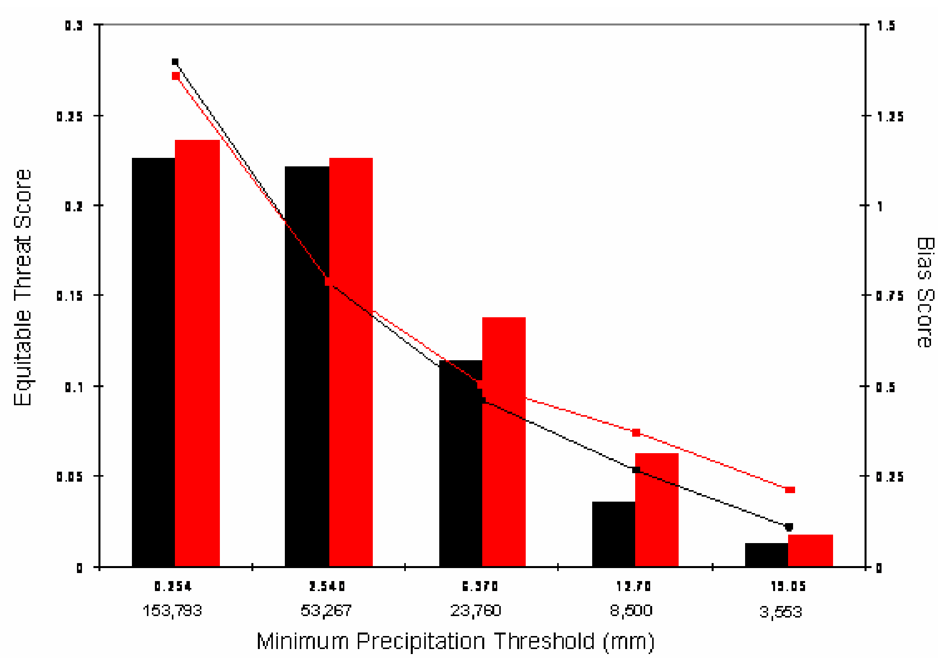

Figure 5: **Long-term statistics of equitable threat score (ETS; bars; left axis) and bias scores (lines; right axis) for 6-h cumulative precipitation ending at the 36-h forecast. The black bars and black line represent the CNTL run, and the red bars and red line represent the AIRS run. The numbers below each threshold indicate how many observed grid points fall in each threshold for the 36-hr forecasts, which is an indication of the significance of the results.**

Figure 5 shows 6-hr cumulative precipitation bias scores and ETS for the 36-hr forecast. For this forecast time, biases are reduced for each threshold when AIRS data are added. For the lowest threshold, the control over-forecasts precipitation (bias score greater than 1), and adding AIRS data lowers the amount of precipitation to more closely match the observations. For the larger thresholds where CNTL under-forecasts precipitation (bias scores less than 1), the AIRS observations improve precipitation coverage. However, an improvement in bias score alone is not enough to show forecast improvement because the bias calculation does not take into account the precipitation location. Similar to the RMSE helping to strengthen the confidence in the bias results, the ETS provides confidence in the bias score results. The ETS for each precipitation threshold is increased (i.e. improved) with the addition of AIRS profile data. What this indicates is that the improvements to the overall precipitation forecast (of simply forecasted versus observed points as indicated with the bias scores) seen with the inclusion of AIRS data is not due chance.

As with the temperature and mixing ratio verification, the results seen at this one forecast time are representative of all forecast times.

CONCLUSIONS/FUTURE WORK

Through extensive case study work (Chou et al. 2006, 2007) and now through investigating long-term statistics of 33 days of near-real-time forecasts, it has been shown that AIRS profiles can improve short-term forecasts of sensible weather parameters. This work has used the ARPS Data Analysis System (ADAS) to assimilate Version 5 AIRS temperature and moisture profiles into a regional domain of the Weather Research and Forecasting (WRF) model. Through assessment of control forecasts that contain no assimilated data and forecasts that have assimilated AIRS profiles with rawinsonde observations and NCEP Stage IV precipitation data, it has been shown that forecasts systematically improve with the addition of AIRS profiles.

Future work involves migrating to a three-dimensional variational assimilation system (e.g. WRF-Var or GSI). The current analysis system does not provide for changes to the mass fields (e.g. winds) when changes are made to the thermodynamic fields. Also, ADAS can not be run in parallel, which significantly increases the time that new initial conditions and forecasts can be generated. The end result of this project is to provide updated initial conditions that contain AIRS observations to National Weather Service (NWS) Weather Forecast Offices (WFO) for use in their local WRF model runs.

ACKNOWLEDGMENTS

The authors would like to thank Tsengdar Lee of NASA Headquarters for funding this project. The authors would also like to thank Kate LaCasse, Jonathan Case, and Will McCarty for their ideas and assistance on this project.

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