Regional Precipitation Forecast with Atmospheric InfraRed Sounder (AIRS) Profile Assimilation

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1. Introduction

Advanced technology in hyperspectral sensors such as the Atmospheric InfraRed Sounder (AIRS; Aumann et al. 2003) on NASA's polar orbiting Aqua satellite retrieve higher vertical resolution thermodynamic profiles than their predecessors due to increased spectral resolution. Although these capabilities do not replace the robust vertical resolution provided by radiosondes, they can serve as a complement to radiosondes in both space and time. 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 AIRS radiances significantly improved 500 hPa anomaly correlations in medium-range forecasts of the Global Forecast System (GFS) model. McCarty et al. (2009) demonstrated similar forecast improvement in 0-48 hour forecasts in an offline version of the operational North American Mesoscale (NAM) model when AIRS radiances were assimilated at the regional scale. Reale et al. (2008) showed improvements to Northern Hemisphere 500 hPa height anomaly correlations in NASA's Goddard Earth Observing System Model, Version 5 (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 profiles into a regional configuration of the Advanced Research Weather Research and Forecasting (WRF-ARW) model using its three-dimensional variational (3DVAR) assimilation system (WRF-Var; Barker et al. 2004). Section 2 describes the AIRS instrument and how the quality indicators are used to intelligently select the highest-quality data for assimilation. Section 3 presents an overall precipitation improvement with AIRS assimilation during a 37-day case study period, and Section 4 focuses on a single case study to further investigate the meteorological impact of AIRS profiles on synoptic scale models. Finally, Section 5 provides a summary of the paper.

2. Methodology

a. AIRS and Assimilation Technique

The AIRS and Advanced Microwave Sounding Unit (AMSU) 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 (Aumann et al. 2003).

Globally, Version 4 AIRS retrieved profiles—compared to radiosondes collocated in time and space—exhibit root mean square (RMS) errors of 1 K in 1-km layers for temperature and 15% relative humidity in 2-km layers for water vapor (Tobin et al. 2006; Divakarla et al. 2006). Here, 28-level temperature and moisture standard retrievals are used to provide the optimal compromise between the superior vertical resolution of AIRS over other instruments while simultaneously reducing the correlations between successive vertical levels and overlapping weighting functions. Errors in the Version 5 profiles are expected to be similar to (if not smaller than) Version 4 (Joel Susskind, personal communication).

In this study, a quality indicator (QI), P_{best}, is used to select the optimal data from each profile for assimilation. Susskind (2006) defines P_{best} as the highest atmospheric pressure level

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(lowest altitude) at which the error estimate for three consecutive pressure levels is not greater than a pre-determined, pressure-dependent error estimate threshold. A larger threshold is used for soundings over land than for soundings over water (Susskind et al. 2006). 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. A representative three-dimensional distribution of AIRS profile locations and their corresponding P_{best} value for 12 Febuary 2007 is shown in Fig. 1 with each colored pixel representing the 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 soundings are located over the ocean, as indicated by the areas of black pixels in Fig. 1.

AIRS profiles are assimilated where appropriate in partly cloudy scenes or above cloud levels based on the P_{best} QIs. Because land soundings have possible surface emissivity contamination and a larger threshold used in calculating the QIs, land and water soundings are assigned separate observation errors in the assimilation process. Guidance from instrument accuracy and validation of AIRS profiles with *in situ* observations are used to assign observation errors for each data type. Observation errors for over-land AIRS profiles are assigned according to validation against Southern Great Plains radiosonde data described in Tobin et al. (2006). On the other hand, the Tropical Western Pacific validation in Tobin et al. (2006) is not representative of the mid-latitude WRF domain, so the AIRS instrument specifications are instead used for water soundings. A summary of the AIRS profile errors and background error (see Section 2b) used in the assimilation process is presented in Fig. 2.

b. Analysis Configuration: WRF-Var

WRF-Var (Barker et al. 2004) is the 3DVAR data assimilation system of WRF, which estimates the true state of the atmosphere by minimizing a cost function that statistically blends a previous forecast (background), observations, and their respective errors. At each analysis grid point, these errors define the weighting of the background and observations.

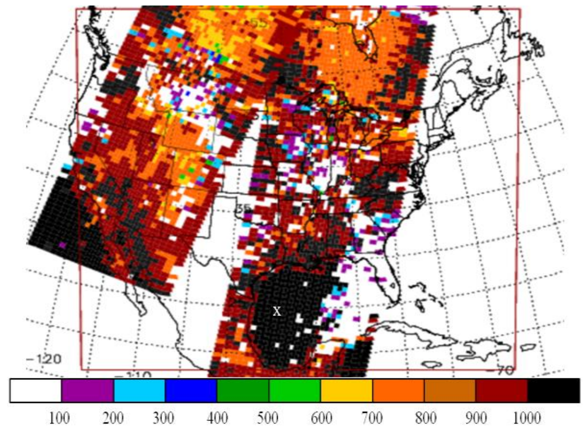

Fig. 1. Quality indicators for AIRS profiles assimilated at 0900 UTC on 12 February 2007. The black points represent the highest quality data, and each colored box denotes the pressure level above which there are quality data. The red rectangle denotes the bounds of the WRF model domain. The "X" denotes the location of the sounding comparison shown in Fig. 5.

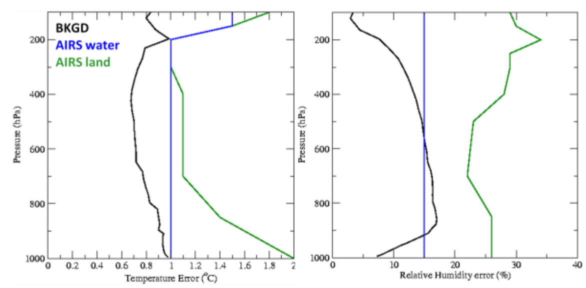

Fig. 2. Background error (black) and observation errors (AIRS-water: blue; AIRS-land: green) for temperature (left) and relative humidity (right) used for the WRF-Var analyses.

Correct calculation and use of the background error covariance matrix (**B** matrix) is crucial in determining the appropriate weight between the background and observations and how information is spread to surrounding grid points. Ideally, background errors should represent the synoptic pattern of the day and be calculated using the background model on the analysis grid. As a result, a **B** matrix created using the National Meteorological Center (NMC) method (Parrish and Derber 1992) and control runs from the 37-day case study period is used. The NMC method assumes that the background error covariances are well approximated by averaged forecast differences between two forecasts verified at the same time. Here differences between 24-h WRF control (*i.e.* no data assimilated) forecasts initialized at 0000 UTC and 12-h WRF control forecasts initialized at 1200 UTC are used to calculate the **B** matrix. The black line in Fig. 2 shows the resulting background error values as a function of pressure averaged over the entire domain.

c. Model Configuration: Advanced Research WRF

Version 2.2.1 of the Advanced Research WRF (ARW) model is used for this study. The The major physical parameterization options used for this study are summarized in Table 1. The analysis and model domains are identical with a 12-km spacing consisting of a 450 x 360 grid that covers the contiguous United States, Western Atlantic Ocean, and Gulf of Mexico (see red box in Fig. 1). The model top is 50 hPa. The vertical domain has 50 staggered terrain-following levels with the finest resolution near the lower boundary and adequate resolution near the domain top to appropriately resolve small-scale vertical features in the model initialization for the best possible analysis background. Further description on the need to appropriately define adequate model vertical levels can be found in Chou (2010, manuscript submitted to *NWA Electronic. J. Operational Meteor.*).

Each WRF forecast is initialized at 0000 UTC using a "cold start" from the 40-km North American Mesoscale (NAM) analysis. A short-term WRF forecast is then run from the initialization time to the observation time of the AIRS profiles, which is determined by the mean of the two AIRS data swaths over central and eastern North America rounded to the nearest hour. This short-term forecast is used as the background field for the WRF-Var analysis. 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 with boundary conditions updated every 3 hours using NAM forecasts. Because the goal of the project is to determine the impact of AIRS profiles on analyses, no other *in situ* observations, satellite radiances, or other satellite profiles are assimilated in either run.

Table 1: Summary of WRF physical options

Microphysics	Ferrier (new Eta)
Longwave Radiation	RRTM
Shortwave Radiation	Dudhia
PBL Scheme	MYJ
Convective Scheme	Kain-Fritsch
Soil Scheme	4-layer Noah LSM

3. Overall Impact on 6-hour Accumulated Precipitation Forecasts

Two sets of forecasts—one with AIRS (AIRS) and one without AIRS (CNTL)—are run for a case study period from 17 January to 22 February 2007 consisting of 37 separate 48-hour forecasts to develop statistics of precipitation data to determine the overall impact from AIRS profiles on qualitative precipitation forecasts (QPF).

The AIRS and CNTL 6-h accumulated precipitation forecasts are verified against 4-km NCEP Stage IV 6-h accumulated precipitation rain gauge and radar composite product mapped to the model grid. Bias scores and equitable threat scores (ETS) (Hamill 1999) are used to determine the skill of the AIRS and CNTL precipitation forecasts. The bias score is simply the ratio of the number of observed points to the number of forecasted points that exceed each threshold value and is a measure of how accurate the forecast predicts the precipitation coverage. The ETS indicates how well the forecasted rainfall region matches the observed rainfall region by accounting for forecast hits and misses that exceeds a given threshold. ETS is a good indicator of whether forecasts are improved over persistence or random correct guesses.

The 6-h accumulated precipitation statistics are generated every 6 hours starting with the 18-h forecast. Bias scores and ETS are calculated on the final tallies covering all grid points east of 105^{o}W longitude over all 37 case study days and all forecast hours for a total of over 13 million validation grid points. Based on the bias scores in Fig. 3, the CNTL runs over-forecast precipitation at the lower thresholds and under-forecast precipitation at the higher thresholds; however, the AIRS runs produce less light rain areas and more heavy rain areas, which results in statistically improved forecast coverage. Enhanced instability resulting from assimilation of AIRS profiles (discussed in more detail in Section 4) likely aids in production of larger quantities of precipitation at the highest precipitation thresholds, which leads to forecast improvement of heavy rainfall events. Improvement is not only noted in the coverage of precipitation forecasted but also in the location of the forecasted precipitation. With the

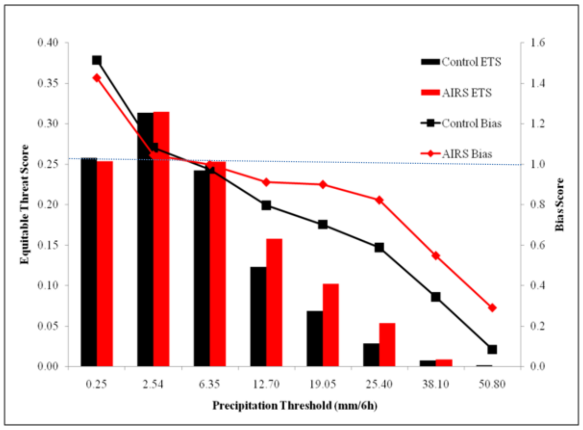

Fig. 3. Six-hourly accumulated precipitation statistics for the 37-day case study period combining all 6-hourly forecasts from 18 to 48 hours. The bars represent equitable threat scores (left axis) and the lines represent bias scores (right axis). White bar and dashed line are for the CNTL runs; black bar and solid line are for the AIRS runs.

exception of the lightest rain rate, the ETS for each precipitation threshold is increased with the assimilation of AIRS profile data (Fig. 3). The best results are for moderate thresholds where the ETS of the AIRS forecasts improves by 28% at amounts greater than 12.7 mm $6h^{-1}$, 14% at 19.05 mm $6h^{-1}$, and 90% at 25.40 mm $6h^{-1}$ over the CNTL. These results indicate that assimilation of AIRS profiles improves both the forecast coverage and locations of precipitation for virtually all precipitation thresholds.

4. Case Study of 12-13 February 2007 Severe Weather Outbreak

Forecasts from 12-13 February 2007 are used to illustrate how increased instability and moisture with the assimilation of AIRS profiles seen in the overall statistics affect an individual forecast of a severe weather and heavy rainfall over the Gulf of Mexico coast. On 12 February at 1200 UTC, a low pressure center was located in Northern Texas and New Mexico and moved eastward across the Great Plains resulting in heavy rain, hail, and wind damage from a convective line of thunderstorms across Eastern Texas and Western Louisiana. Late on 12 February and into 13 February, there were numerous tornado, high wind, and hail reports extending from southeastern Texas into southern Louisiana and southern Mississippi resulting in 2 fatalities and dozens of injuries. These storms occurred approximately 24 hours after the assimilation of AIRS profiles on 12 February 2007. Clear skies ahead of the front and over the data-void Gulf of Mexico on 12 February allowed for high-quality AIRS data to be assimilated all the way to the surface for a complete sampling of the pre-frontal environment (Fig. 1). The 6-h accumulated precipitation reaches its peak around 0000 UTC 13 February with greater than 50 mm of rain falling over Eastern Texas (Fig. 4c). While the CNTL forecast (Fig. 4a) produces some rainfall over Eastern Texas, it fails to capture the intensity of precipitation associated with the convective line. Assimilating AIRS temperature and moisture profiles increases the intensity of the maximum 6-h precipitation from 30 mm to 45 mm (Fig. 4b), which is a more comparable forecast to the Stage IV observations than the CNTL. Additionally, the spatial distribution of the heavy rainfall band in the AIRS forecast is a better match to the Stage IV rainfall than the CNTL

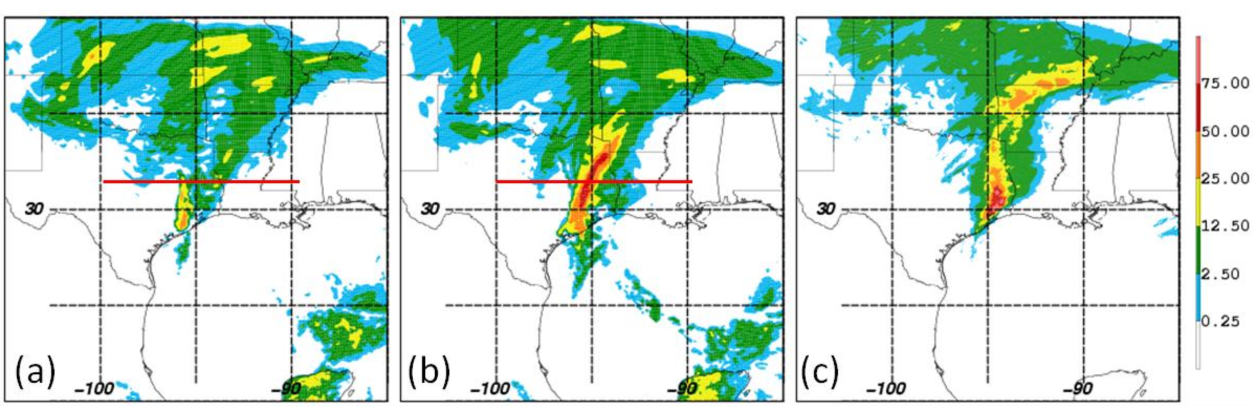

Fig. 4. The 6-h accumulated precipitation valid at 0000 UTC 13 February 2007 for (a) the CNTL prediction, (b) the AIRS prediction, and (c) Stage IV analysis. The lines represent the cross-sections shown in Fig. 7.

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The improved precipitation forecast over Eastern Texas is the result of increased instability provided by the AIRS assimilation. Figure 5 shows the impact of AIRS profiles on the analysis sounding from the Western Gulf of Mexico pre-convective environment (marked X in Fig. 1) at 0900 UTC 12 February. Assimilation of AIRS profiles (blue lines) produces an analysis (red lines) that is warmer in the boundary layer but cooler in the mid-troposphere than the background (black lines). The AIRS profiles also make the atmosphere more humid throughout the entire atmospheric column. The resultant warming and moistening in the lower layers with the assimilation of AIRS profiles creates a more unstable atmosphere, which leads to favorable conditions for convection over the Western Gulf of Mexico. Addition of AIRS profiles contributes to an increase in magnitude (from 1200 J kg^{-1} to 1800 J kg^{-1}) and better representation of the spatial distribution of higher convective available potential energy (CAPE) values over the Western Gulf of Mexico than the CNTL analysis (Fig. 6), which is more consistent with the verifying NAM analysis (not shown). Consequently, the AIRS forecasts produce lower level moisture, vertical velocities, and instability that are more conducive for convection than the CNTL forecast. Figure 7 shows the vertical cross-section (line in Fig. 6) of vertical velocity ($\omega=dp/dt$), equivalent potential temperature, mixing ratio, and 85% RH contour across the line of convective storms in Eastern Texas. The AIRS forecast (Fig. 7b) has higher low-level moisture near the surface and a more unstable equivalent potential temperature profile near the rain band than the CNTL (Fig. 7a). It also shows a near saturation in the convective core which facilitates the release of moist instability and contributes to the intensive updraft in the AIRS forecast. The convection is propelled by the advance of low-layer moisture return flow from the Gulf of Mexico as well as the increase of moist instability in this region resulting in two strong updrafts in the AIRS simulation (one near the surface and another in the mid- to upper atmosphere slightly east of the first) that appear only as a single weak updraft in the CNTL forecast.

For this 12-13 February 2007 case study over Eastern Texas, inclusion of AIRS temperature and moisture profiles in data void regions results in greater model instability and

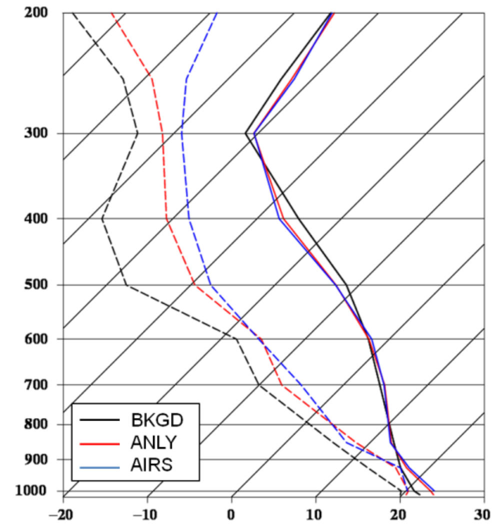

Fig. 5. Temperature and moisture sounding profiles at (24^{o}N; 94^{o}W) at 0900 UTC 12 February 2007. Black lines represent the background, red lines represent the WRF-Var analysis, and blue lines represent the AIRS profile data. Black lines are for temperature and gray lines dew point temperature.

improved forecast of convective precipitation. The resulting squall line that produced deadly tornadoes across parts of the Gulf of Mexico coast is more intense in the AIRS case than in the CNTL. This case also highlights that it is crucial for the high-quality AIRS data to be at the right place and right time to have the maximum impact. The high-quality AIRS profiles are located downstream of the flow driving the convection for this set of storms ahead of the approaching low pressure system and front, which allows information assimilated over the Gulf of Mexico to propagate towards the forecast location of the convective storms. However, if the AIRS swaths for that date were in a different location or cloudy skies prevented high-quality AIRS profile data from being assimilated near the surface, the impact on the precipitation may have been reduced. As a counterexample to the case presented above, the next assimilation cycle on 0800 UTC 13 February shows little impact from AIRS on the precipitation forecast as the front continues to march eastward across the Southeastern United States. Although clear skies still prevail over the Central and Western Gulf of Mexico, the location of the AIRS swaths is such that there is a gap between the eastern and central swaths over the Central Gulf of Mexico in the warm sector of the storm resulting in limited impact from the AIRS profiles.

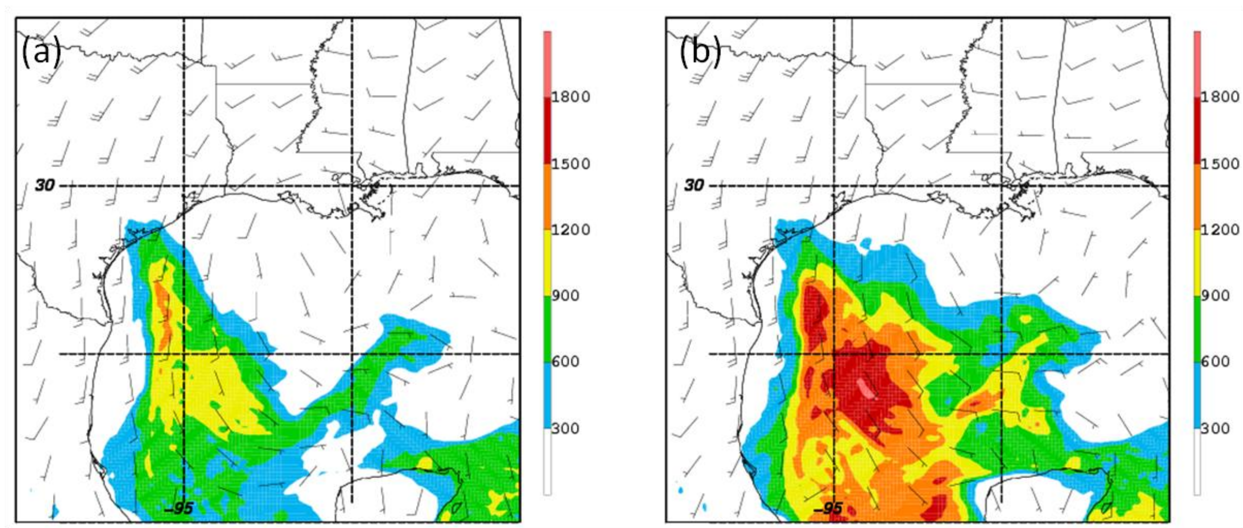

Fig. 6. Spatial distribution of convective available potential energy (CAPE) at 0900 UTC 12 February 2007 for the (a) CNTL and (b) AIRS runs. The 850 hPa wind barbs (m s^{-1}) indicate the prevailing southern flow.

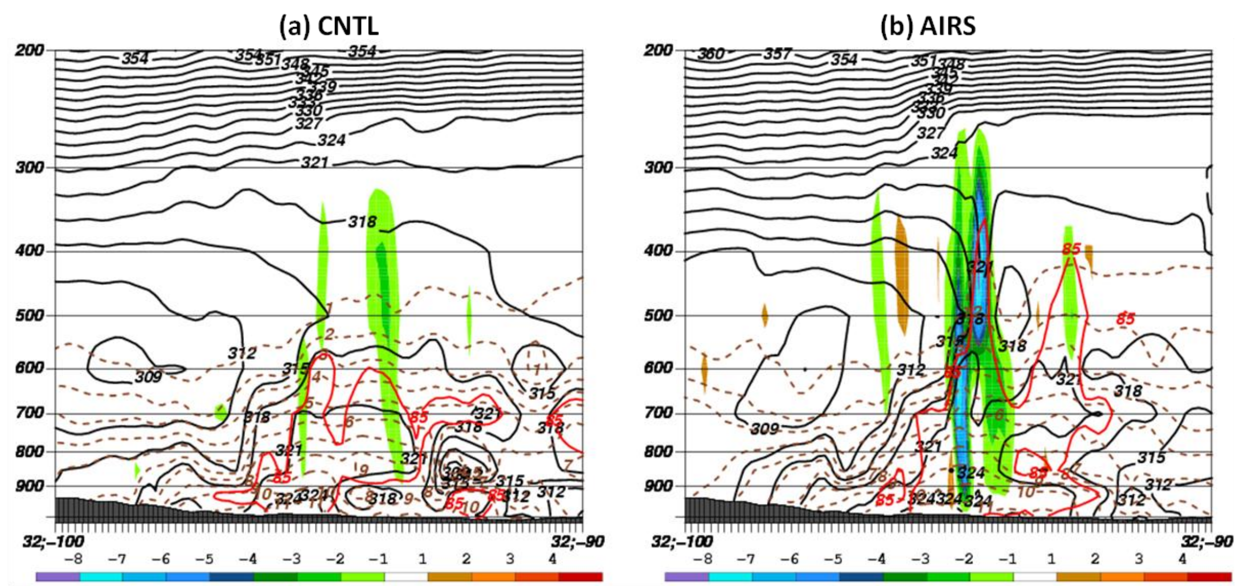

Fig. 7. Vertical cross-section of vertical velocity (hPa s^{-1}; color shaded), equivalent potential temperature (^{o}C; black), mixing ratio (g kg^{-1}; brown), and 85% RH contour (red) along 32^{o}N between 100^{o}W and 90^{o}W (straight line in Fig. 6) for the (a) CNTL and (b) AIRS runs.

6. Summary

A methodology for assimilating Version 5 Level-II AIRS thermodynamic profiles into WRF using WRF-Var has been shown to improve short-term regional forecasts by filling spatial and temporal data gaps using observations from NASA polar-orbiting satellites. A short-term WRF forecast is used as the background for the analysis, and quality indicators are used to select only the highest quality AIRS data, which are assimilated as separate land and water soundings. When assimilated, AIRS profiles produce an analysis that is a consistent blend of the model background and observations, which in many cases is more representative of collocated radiosondes than the background. The AIRS-enhanced initial conditions result in increased instability forecasts compared to CNTL forecasts from a 37-day case study period from the winter of 2007 based on temperature and mixing ratio bias verified against the NAM. This enhanced instability results in improved precipitation for moderate to heavy rainfall thresholds when validated against NCEP Stage IV precipitation analyses. The AIRS profiles have a large positive impact on precipitation intensity and location for a squall line severe weather outbreak over Eastern Texas and Louisiana for one case where flow from the Gulf of Mexico produced high instability across the Gulf Coast. Assimilation of the AIRS profiles resulted in enhanced lower level moisture, CAPE, and vertical velocity to produce a better representation of the squall line than appears in the CNTL. Positive impacts of inclusion of AIRS profiles over the Gulf of Mexico and southeast United States is encouraging for possible future application of analyses incorporating AIRS profiles in detecting moisture return and instability over the Gulf of Mexico and points downstream.

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REFERENCES

Aumann, H. H., M. T. Chahine, C. Gautier, M. D. Goldberg, E. Kalnay, L. M. McMillin, H. Revercomb, P. W. Rosenkranz, W. L. Smith, D. H. Staelin, L. L. Strow, and J. Susskind, 2003: AIRS/AMSU/HSB on the Aqua Mission: Design, Science Objectives, Data Products, and Processing Systems. *IEEE Transactions on Geoscience and Remote Sensing*, **41**, 253-264.

Barker, D. M., W. Huang, Y.-R. Guo, A. J. Bourgeois, and Q. N. Xiao, 2004: A Three-Dimensional Variational Data Assimilation System for MM5: Implementation and Initial Results. *Mon. Wea. Rev.*, **132**, 897-914.

Derber, J. C. and W-S. Wu, 1998: The Use of TOVS Cloud-Cleared Radiances in the NCEP SSI Analysis System. *Mon. Wea. Rev.*, **126**, 2287-2299.

Divakarla, M. G., C. D. Barnet, M. D. Goldberg, L. M. McMillin, E. Maddy, W. Wolf, L. Zhou, and X. Liu, 2006: Validation of Atmospheric Infrared Sounder temperature and water vapor retrievals with matched radiosonde measurements and forecasts. *J. Geophys. Res.*, **111** D09S15, doi:10.1029/2005JD006116.

Errico, R., 1999: Workshop on assimilation of satellite data. *Bull. Amer. Meteor. Soc.*, **80**, 463-471.

Hamill, T. M., 1999: Hypothesis Tests for Evaluating Numerical Precipitation Forecasts. *Wea. Forecasting*, **14**, 155-167.

Le Marshall, J., J. Jung, J. Derber, M. Chahine, R. Treadon, S. J. Lord, M. Goldberg, W. Wolf, H. C. Liu, J. Joiner, J. Woollen, R. Todling, P. van Delst, and Y. Tahara, 2006: Improving Global Analysis and Forecasting with AIRS. *Bull. Amer. Met. Soc.*, **87**, 891-894.

McCarty, W. M., G. Jedlovec, and T. Miller, 2009: The Impact of the Assimilation of AIRS Radiance Measurements on Short-term Weather Forecasts. *J. Geophys. Res.*, **114**, D18122, doi:10.1029/2008JD011626.

Parrish, D.F. and J.C. Derber, 1992: The National Meteorological Center's Spectral Statistical-Interpolation Analysis System, *Mon. Wea. Rev.*, **120**, 1747-1763.

Reale, O., J. Susskind, R. Rosenberg, E. Brin, E. Liu, L.P. Riishojgaard, J. Terry, and J.C. Jusem, 2008: Improving forecast skill by assimilation of quality-controlled AIRS temperature retrievals under partially cloudy conditions. *Geophys. Res. Lett.*, **35**, **L08809**, doi: 10.1029/2007GL033002, 6 pp.

Singh, R. K. Pal, C.M. Kishtawal, and P.C. Joshi, 2008: Impact of Atmospheric Infrared Sounder Data on the Numerical Simulation of a Historical Mumbai Rain Event. *Wea. Forecasting*, **23**, 891-913.

Susskind, J., 2006: Improved soundings and error estimates using AIRS/AMSU data. *Proc. SPIE Int. Soc. Opt. Eng.*, **6233**, 19, 12 pp.

Susskind, J., C. Barnet, J. Blaisdell, L. Irdell, F. Keita, L. Kouvaris, G. Molnar, and M. Chahine, 2006: Accuracy of geophysical parameters derived from Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit as a function of fractional cloud cover, *J. Geophys. Res.*, **111**, D09S17, doi:10.1029/2005JD006272.

Tobin, D. C., H. E. Revercomb, R. O. Knuteson, B. M. Lesht, L. L. Strow, S. E. Hannon, W. F. Feltz, L. A. Moy, E. J. Fetzer, and T. S. Cress, 2006: ARM site atmospheric state best estimates for AIRS temperature and water vapor retrieval validation. *J. Geophys. Res.*, **111**, D09S05, doi:10.1029/2005JD006095.