P1.3 The Impact of Atmospheric InfraRed Sounder (AIRS) Profiles on Short-term Weather Forecasts

Shih-Hung Chou*
NASA/Marshall Space Flight Center, Huntsville, AL

Bradley Zavodsky
Earth Science System Center, University of Alabama in Huntsville, Huntsville, AL

Gary Jedlovec, William Lapenta
NASA/Marshall Space Flight Center, Huntsville, AL

1. INTRODUCTION

Significant weather events regularly occur in regions downstream of sparse data (e.g. coastlines, deserts, large forests, etc.) and without adequate observations, meteorological analyses often revert to the background (i.e. first guess) field. Observations from satellites are one valuable option to complement traditional atmospheric observations in these regions. Currently, the most state-of-the-art atmospheric profiler is the Atmospheric InfraRed Sounder (AIRS). AIRS radiances have been assimilated into global models yielding improvements in 500 hPa anomaly correlations out to 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.

Previously, Chou et al. (2006) assimilated AIRS version 4.0 thermodynamic profiles for a Pacific storm case. These results showed that the AIRS data impacted the analysis and resulted in positive forecast impact on temperature and moisture when compared to west-coast rawinsonde data. This paper focuses on a new case study using similar methodology whereby a rapidly developing cyclone incubated over the Gulf of Mexico impacts the eastern half of the United States over a 60-hour timeframe. Section 2 contains a description of the AIRS data used for this study. Section 3 contains a brief overview of the Advanced Regional Prediction System (ARPS; Xue et al., 2001) Data Assimilation System (ADAS; Brewster 1996) used to assimilate the AIRS profiles and the Weather Research and Forecasting (WRF; Skamarock 2005) numerical model. Section 4 describes the meteorological conditions of the case study and the sensitivity experiments to be conducted. Section 5 includes preliminary results from the case study with Section 6 containing conclusions and future work.

Corresponding author address: Shih-hung Chou, 320 Sparkman Dr., Huntsville, AL, 35805; e-mail: shih.h.chou@nasa.gov

2. AIRS DESCRIPTION

Aboard the EOS polar-orbiting Aqua satellite with an early afternoon equator 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 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.

For this study, we use a set of prototype version 5.0 soundings that contain improvements in the radiative transfer algorithm and quality control flags over the version 4.0 data currently available at the Goddard Distributed Active Archive Center (DAAC). Each sounding contains approximately 54 vertical levels between the surface and 100 hPa. Although these new version profiles have not yet been validated, it is expected that the relative validation errors will be similar to (or better than) those presented for the version 4.0 data (Susskind, personal communication).

Globally, the AIRS version 4.0 retrieved profiles—compared to rawinsondes collocated in time and space—exhibit RMS errors of 1K in 1-km layers for temperature and 10-15% RH in 2-km layers for water vapor (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 overland scenes.

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 assemble the AIRS data into various assimilation experiments to determine the optimal AIRS data configuration (see Section 4.3). A three-dimensional distribution of AIRS profiles assimilated in this study—with pressure-dependent quality indicators—is shown in Figure 1. The reader should refer to Susskind et al. (2006) for more information on how the quality indicators are generated. Optimal use of these quality indicators will enable assimilation of only the highest quality data and are expected to yield improved forecasts in the 0- to 60-hour time frame.

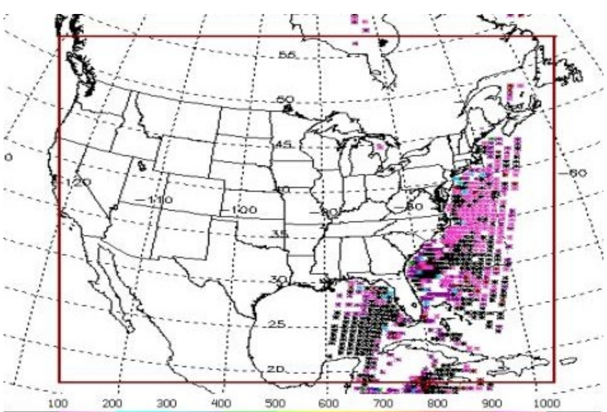

Fig. 1. Three-dimensional distribution of AIRS profile data assimilated at 0700 UTC on 20 November 2005. The black points represent the highest quality data. Each colored point denotes the maximum pressure level corresponding to the level above which data is of good quality. The red rectangle denotes the bounds of the WRF/ADAS domain.

3. ANALYSIS AND FORECAST MODELS

3.1. ARPS Data Analysis System (ADAS)

The ADAS (Brewster 1996) provides a means to merge different sources of local meteorological data into a coherent three-dimensional description of the atmosphere and has been configured to assimilate satellite profiles from AIRS. This particular analysis system was selected for its flexibility and ease of configuration for satellite-derived atmospheric profiles. In this study, only AIRS data is used to produces the analyses. No other data sets (e.g. MADIS data) are assimilated.

The ADAS uses a Bratseth (1986) successive correction methodology that employs a ratio of the background and observation error covariances to calculate each analyzed field. These covariances are a combination of instrument/model error and representativeness error (i.e. error attributed to inaccuracies introduced due to differences between the resolution of the observations and the grid resolution). The 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 are based on estimates cited by Tobin et al. (2006) for a Tropical Western Pacific (TWP) validation experiment of version 4.0 profiles. For reference, the observation covariance values typical for rawinsondes are about twice as large as the AIRS for temperature and about two-thirds smaller for moisture.

Horizontal and vertical scaling factors, which determine the amount of smoothing for each observation in the analysis, were also configured. Scaling factors should be selected such that information from enough observations can be combined without the data becoming decorrelated over large scaling distances. The horizontal scaling factors are reduced in subsequent iterations to ensure convergence (Lazarus et al. 2002). Three iterations of the Bratseth scheme are performed with horizontal scaling factors of 150, 120, and 100 km, respectively. The vertical scaling factors smooth data between pressure levels. Based on the vertical resolution of the data and the layer-averages that each AIRS level represents, this value is fixed at 750 m for the first two iterations and reduced to 400 m for the final iteration. The largeness of the vertical scaling factor mitigates some of the impact of using layer-averaged data in a fashion similar to point data. Again, for reference, rawinsondes typically are scaled at 300 km and 120 km in the horizontal and 500 m and 300 m in the vertical, further illustrating

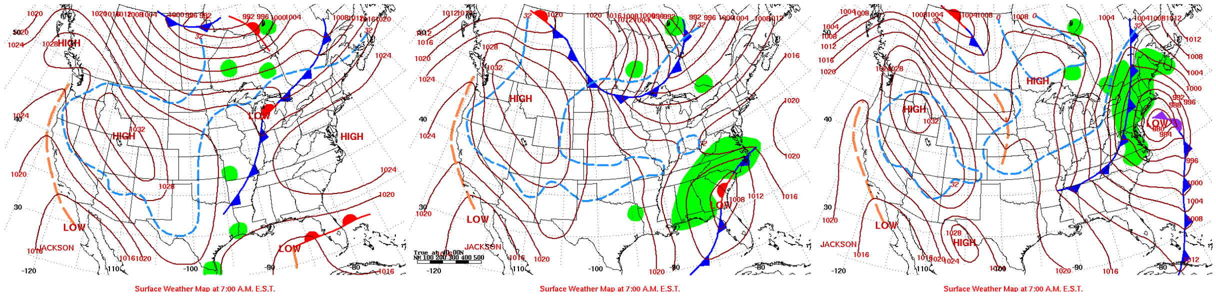

Fig. 2. Surface weather maps showing the development/track of a low-pressure system from the Gulf of Mexico across northern Florida and southern Georgia and into the Atlantic Ocean south of Long Island after 48 hours. The left panel shows the 1200 UTC conditions on 20 November 2005, the center panel shows the 1200 UTC conditions on 21 November 2005, and the right panel shows the 1200 UTC conditions on 22 November 2005.

the finer horizontal resolution and layer nature of the AIRS profiles.

3.2. 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 150 x 120 grid with 36-km spacing and covers the contiguous United States, Western Atlantic Ocean, and Gulf of Mexico (see Fig. 1). It has 37 staggered terrain-following sigma levels with the top-level pressure at 100 hPa and finest resolution near the boundary layer.

The WRF physical options used in this study consist of the Ferrier (new Eta) microphysics, the Kain-Fritsch cumulus convection scheme (Kain and Fritsch 1990), and the Yonsei University (YSU) planetary boundary layer scheme (Hong et al. 2006). The rapid radiative transfer model (RRTM, Mlawer et al. 1997) and Dudhia scheme (Dudhia 1989) are used for longwave and shortwave radiation, respectively, while the four-layer Noah land surface model (Chen and Dudhia 2001) provides the land surface physics.

4. EXPERIMENT DESIGN

4.1. Case Study: 20-22 November 2005

A shortwave disturbance over the northern Gulf of Mexico at 1200 UTC on 20 November 2005 played a significant role in the weather along the east coast of the United States over the following two days. The storm system produced 6h precipitation totals upwards of 65 mm (≈2.5 in.) along its track over the coastal Atlantic states.

The synoptic maps in Figure 2 show 24-hour snapshots—generated by the National Centers for Environmental Prediction (NCEP) and the National Weather Service—of the storm development from 1200 UTC on 20 November 2005 to 1200 UTC on 22 November 2005. At 1200 UTC on 20 November 2005, a ridge of high pressure blanketed most of the eastern seaboard, and a deep upper-level trough was propagating across the middle of the continent with the aforementioned shortwave over the central Gulf of Mexico. Twenty-four hours later, as the upper-level trough entered the Eastern states, the surface low began to deepen over Florida and Georgia. The storm moved quickly up the coast and deepened to 980 hPa by 1200 UTC on 22 November off the coast of Delaware and New Jersey.

This particular storm system is of interest because of its proximity to the Southeastern United States and its genesis in a relatively data void region (over the Gulf of Mexico and western Atlantic Ocean). It is expected that AIRS profiles should have their most significant impact on the ADAS analyses used to initialize the WRF. Another positive feature of this case study is that there is an Aqua overpass at a time prior to storm development and in the location of the storm path meaning there is plenty of clear and partly cloudy skies in the Gulf and western Atlantic providing good coverage of high-quality AIRS data.

4.2. WRF/ADAS Coupling

The forecast/analysis cycles for the AIRS-assimilated runs are shown in Figure 3. The WRF is initialized with the North American Mesoscale (NAM) analysis, which is available every six hours. The boundary conditions are updated every 3 hours using the NAM forecasts. The WRF/ADAS assimilation cycle begins at 0600 UTC on 20 November 2005 with a 1-hour forecast. This forecast is then used as the first guess field for the ADAS analysis at 0700 UTC when the AIRS profiles in our forecast domain become available. The ADAS analysis initializes the WRF for the AIRS-assimilated runs and produces a total forecast of 60 hours—the same length as the NAM forecast cycle. The control run uses the same NAM analysis and model forecasts for the initial and boundary conditions, respectively, but does not incorporate ADAS.

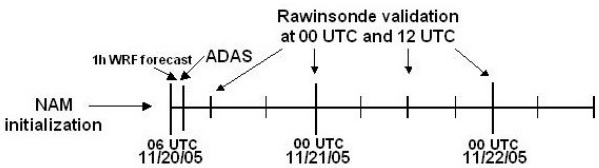

Fig. 3. ADAS/WRF forecast cycle schematic.

4.3. Sensitivity Experiments

Since the quality of over-land profiles is still not certain due to surface emissivity issues, only AIRS data over water were used for these experiments. Recall that Figure 1 shows the three-dimensional depiction of the AIRS profile data at 0700 UTC on 20 November 2005. The color at each location indicates the maximum pressure level above which the AIRS data is valid. All data below the maximum pressure level is of questionable quality. Four numerical experiments were designed to examine the impact on short-term weather forecasts of various sets of quality control flags in the AIRS data:

Control (CNTL): WRF run that does not include any assimilated AIRS data. This represents the base state of our configuration. Forecast improvement will be determined by comparing the various AIRS-assimilated runs to the control.

No Quality Control (NOQC): This experiment uses all levels of all profiles indiscriminately and represents an unintelligent use of the AIRS data.

Use Quality Control (QC): This case uses the quality indicators to eliminate any questionable data. Within this set of AIRS profiles there will be many partial soundings. More data will be available in the upper levels. The valid layers of the soundings are illustrated in Figure 1 with data above the maximum pressure level being assimilated.

Quality Control Subset (QCSUB): This case uses only full AIRS profiles that contain quality data from the surface to the top of the atmosphere. These profiles have a quality-indicated maximum pressure level that is less than 30 hPa from the surface pressure value. Black points in Figure 1 represent the soundings used in this experiment.

5. RESULTS OF SENSITIVITY EXPERIMENTS

5.1 Rawinsonde Verification

The upper-air verification statistics for the forecast are computed, at 0000 and 1200 UTC, by comparing the rawinsonde value to the model forecast values interpolated to the location of the rawinsondes. In this study, verifications are based on 17 rawinsonde stations along the eastern seaboard (Fig. 4) where AIRS data should have the largest forecast impact. Overall, the inclusion of AIRS data tends to cool and dry mid- to upper troposphere compared to the control case. The QCSUB and QC cases follow each other closely and have the best statistics among the forecasts. Indiscriminatingly using AIRS data (NOQC) degrades the forecasts but still shows improvement over the control case.

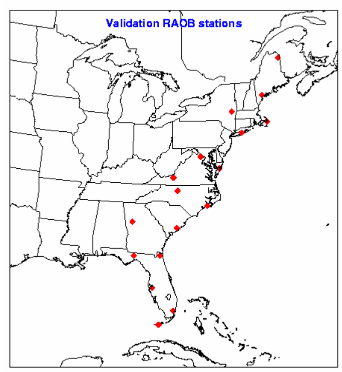

Fig. 4. Rawinsonde locations for verification statistics.

Results for the 42h forecast, which represent typical AIRS impacts on WRF forecast, are presented in Figure 5. Temperature is shown in standard bias and root mean square error (RMSE), while moisture is shown in relative values, which are the standard value normalized by the average observation value. This is done to compensate for low moisture content in the upper levels. The relative bias and RMSE for mixing ratio are defined as

$$rel\_bias = \left[\frac{1}{N}\sum(fcst - obs)\right] / \left[\frac{1}{N}\sum obs\right],$$

$$rel\_RMSE = \left[\frac{1}{N}\sum(fcst - obs)^2\right]^{1/2} / \left[\frac{1}{N}\sum obs^2\right]^{1/2},$$

where N is the total number of observations at a given pressure level.

Figure 5a shows that including AIRS profiles in the analysis has a cooling effect in the mid- to upper troposphere and a slight warming in the lower atmosphere, compared to the control case. The NOQC case produces the largest cooling with a maximum of ~0.5C at 500 hPa. The addition of AIRS data improves the temperature forecast with a ~0.4C RMSE reduction between 500 and 300 hPa, where the BEST and HGHQ cases show most improvement (Fig. 5b). Figure 5c shows a moistening effect at the lower atmosphere and a drying effect at ~400 hPa when AIRS data are added. As in the temperature RMSE, the mixing ratio shows largest positive impacts in mid- to upper troposphere (Fig. 5d). Figure 5 demonstrates that the WRF forecasts with selected AIRS data show improvements over the control forecast. Slight forecast degradations near the surface might be attributable to surface influences in the lower levels of the AIRS radiative transfer algorithm.

5.2 Cumulative Precipitation Verification

Verification of precipitation forecasts are made by comparing the model output precipitation fields with 4-km NCEP Stage IV radar 6h composite data mapped to the WRF model domain for direct comparison. While this provides ample verification data, there are some limitations to using Stage IV data. Foremost, much of the verification data is constrained to over land regions because of radar location, while much of the anticipated impact on the forecasts is expected over water.

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 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 indicates that the precipitation fields are perfectly aligned, and an ETS of 0 means that there are no matches at all.

Precipitation is verified using grid points that lie to the east of 90^{o}W longitude. Figure 6 shows the bias score and ETS for 6h cumulative precipitation totals ending at the 42h forecast (valid at 0000 UTC on 22 November 2005). The 42h forecast is representative of the overall trends in the precipitation forecast for this case study. The bias scores indicate that the forecasts for all four cases overestimate precipitation coverage for light to moderate thresholds at a nearly two-to-one ratio. For larger precipitation thresholds, the QCSUB case significantly over-forecasts precipitation largely due to the small number of observed and forecasted points at higher precipitation thresholds. For the most part, the CNTL, NOQC and QC cases follow the same trends with the QC case performing slightly better at lower precipitation thresholds and slightly worse at moderate precipitation thresholds.

The ETS for the NOQC and CNTL case follow each other closely for most precipitation thresholds indicating either no improvement or slight forecast degradation with the indiscriminate use of AIRS profiles. The ETS for the QC case is as large or larger than all other cases for the lower-to-middle precipitation thresholds while the QCSUB case yields higher ETS at higher thresholds. Overall the combination of the ETS and bias results indicate that addition of the QC AIRS profiles has a positive impact on precipitation forecasts.

6. CONCLUSIONS/FUTURE WORK

This paper has presented a methodology for assimilating prototype v5.0 AIRS thermodynamic profiles into a regional model. Quality indicators were used to subset the AIRS profiles into three experiments (plus a control). The ADAS was used to assimilate the AIRS data using a 1-hour WRF forecast initialized with the NAM as a background. The resultant analysis was then used to initialize a 60-hour model run. Results indicate that temperature and moisture forecasts are improved with the use of AIRS data when compared to collocated east coast rawinsondes. Similarly, accuracy of precipitation forecasts was shown to improve with the use of the highest quality AIRS data defined in the quality indicators. However, which subset of AIRS profiles will maximize the forecast impact remains to be determined.

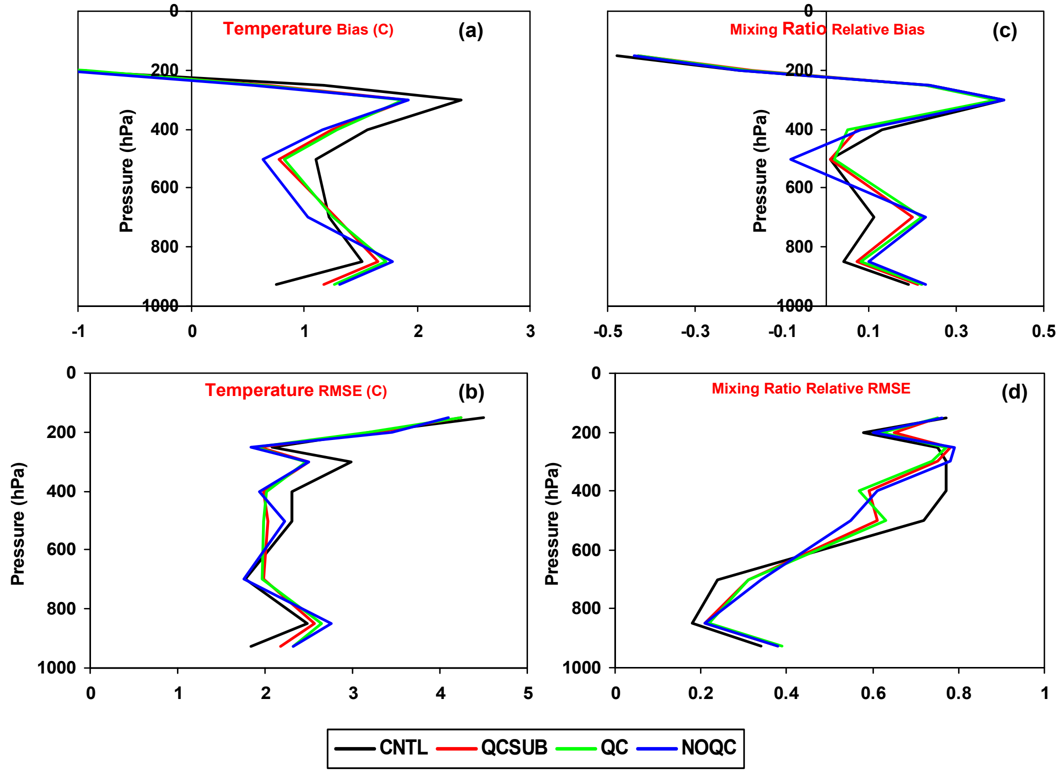

Fig 5. 41-h forecast of (a) temperature bias, (b) temperature RMSE, (c) mixing ratio relative bias, and (d) mixing ratio relative RMSE for the four experiments valid at 00 UTC 22 November 2005.

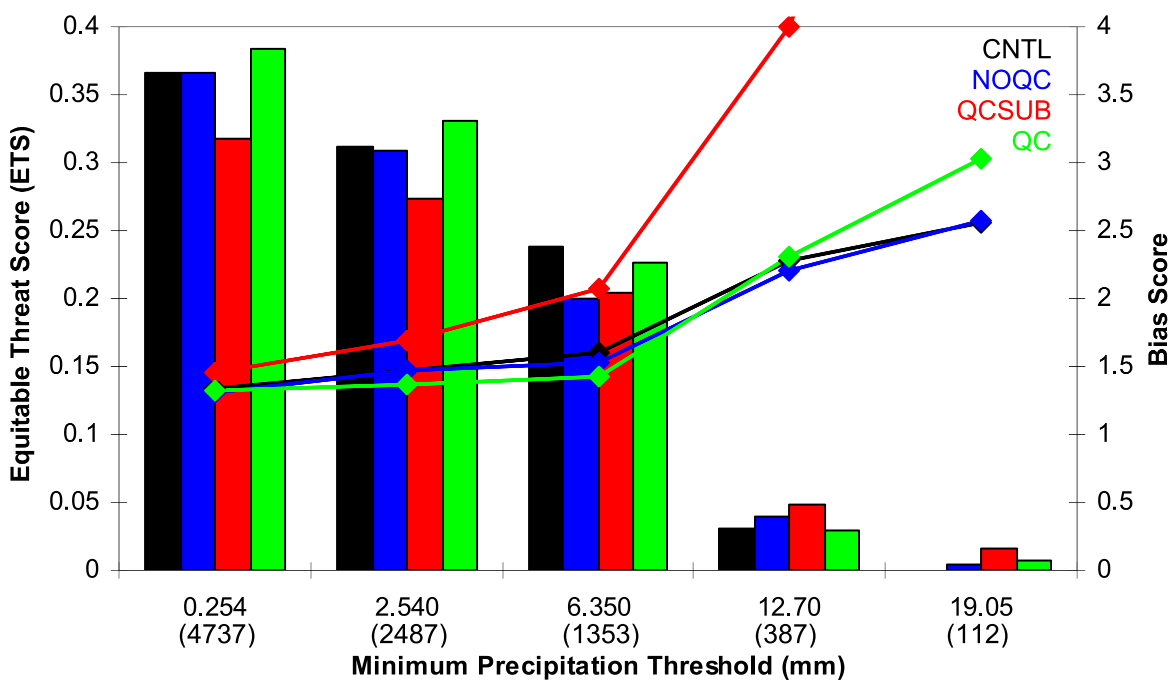

Fig. 6. Equitable Threat Score (ETS; bars) and Bias Score (lines) for precipitation verification. The parenthetical values below each threshold value are the number of grid points in the Stage IV observations greater than that threshold.

Future work will involve a more large-scale verification of temperature, moisture, height, and winds using grid point to grid point comparisons between our WRF forecasts and NAM analyses collocated in time. These comparisons provide a methodology for verifying model impact over water where rawinsonde data is not available.

Version 5.0 of the AIRS thermodynamic profiles will be available in near real time starting in early 2007. Once these profiles are ready, we plan to use these profiles for an extended period (of a month or more) to examine long-term averages of forecast impact and to determine which subset will maximize positive forecast impact. The rationale for a longer case study is that conclusions are difficult to draw from one or two individual case studies. The AIRS data will be assimilated in near real time with similar methodology described in this document. The verification procedures outlined herein, plus the aforementioned verification against NAM analysis, will be used to determine forecast impact.

7. ACKNOWLEDGMENTS

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