P3.1 THE IMPACT OF AMSU-A RADIANCE ASSIMILATION IN THE U.S. NAVY'S OPERATIONAL GLOBAL ATMOSPHERIC PREDICTION SYSTEM (NOGAPS)

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ABSTRACT

The Navy Operational Global Atmospheric Prediction System (NOGAPS) is the U. S. Department of Defense high-resolution global weather prediction system, which is used for operational medium range weather prediction, forcing for operational mesoscale and oceanographic models, and numerical weather prediction (NWP) research. The analysis for NOGAPS is produced by the NRL Atmospheric Variational Analysis System (NAVDAS). On 09 June 2004, NAVDAS began operational assimilation of AMSU-A radiances from the ATOVS sensor suite onboard NOAA 15 and 16 for NOGAPS. The direct assimilation of AMSU-A radiances replaced the assimilation of ATOVS temperature retrievals produced by NESDIS. The results of medium-range forecast tests of radiance assimilation versus NESDIS ATOVS retrieval assimilation show substantial improvement in the forecasts of height, wind, and temperature in both the Northern and Southern Hemispheres. In the Tropics, the tropical cyclone track errors are smaller with radiance assimilation, even though the upper- and lower-level wind errors are essentially the same. Overall, there are fewer forecast "busts" with radiance assimilation, especially in the Southern Hemisphere.

1. INTRODUCTION

One of the primary motivations for developing variational data assimilation systems is the ability to effectively utilize observations that are related nonlinearly or indirectly to the analysis variables (e.g., temperature and u- and v- wind components). With satellite sounder radiances such as those from AMSU-A, the outgoing microwave radiation at the top of the atmosphere at a specific spectral frequency (i.e. channel) is related to the atmospheric temperature and moisture profile (and the surface emissivity and skin temperature) through the radiative transfer equations. Traditionally, the satellite radiances or brightness temperatures have been used to compute retrievals of temperature and humidity profiles. However, the retrieval problem is mathematically ill-posed, both because the brightness temperatures are imperfect and because they do not represent a single level in the atmosphere, but include contributions over deep layers in the atmosphere (as determined by the weighting functions) (Rodgers, 2000). Consequently, retrieval errors are complicated to understand and specify correctly in assimilation systems. In contrast, the errors of the brightness temperature observations are much simpler to characterize.

There are a number of requirements for successful direct assimilation of satellite brightness temperatures, in addition to possession of a three-dimensional variational data assimilation system such as NAVDAS. Radiance assimilation demands that the short term NWP model forecast, which is used as the background, be sufficiently accurate, so that the NAVDAS minimization can converge on a solution. In recent years, NWP models have had to improve to make radiance assimilation more effective. Examples include pushing the model tops up to 0.1 hPa, including ozone chemistry, and improving the model moisture fields and surface skin temperatures over land. Radiance assimilation also demands careful quality control. Because the fast radiative transfer model assumes that atmospheric temperature and brightness temperature are linearly related, we must take care to remove obviously nonlinear observations, such as those contaminated by scattering from hydrometeors. Even after careful quality control, biases in the innovations (observed minus background brightness temperatures) remain, and these are often larger than the signal itself. Finally, we must remove these biases before passing a set of innovations to NAVDAS to produce an analysis. Only if all of these steps are completed, can radiance assimilation fulfill its promise of appreciably improved forecasts.

The payoffs have been substantial. The U.K. Met Office has reported that adding AMSU radiance assimilation led to greater improvements in the forecast accuracy than all model and analysis improvements over a 10-yr period. In this paper, we present the results from several data assimilation tests using both AMSU-A radiances and NESDIS ATOVS retrievals. These results confirm the benefits of AMSU-A radiance assimilation for global NWP.

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2. SUMMARY OF AMSU-A RADIANCE ASSIMILATION

In this section, we give a brief overview of the main components of AMSU-A radiance assimilation, namely the channel selection, data thinning, quality control, bias correction, and aspects of the assimilation problem pertinent for operational assimilation of AMSU-A radiances at FNMOC (Fleet Numerical Meteorology and Oceanography Center).

2.1 *Channel Selection*

The initial design of NAVDAS assumes that the relationship between brightness temperatures and atmospheric temperature is linear; therefore, the quality control and channel selection procedures are designed to assure that this relationship is met.

The channel selection for the initial operational implementation of radiance assimilation is shown in Table 1. Channels 1, 2 3, and 15, which have strong contributions from the surface, clouds and low-level water vapor are used for quality control, but not for assimilation. Channels 12-14 are not assimilated because they peak above the top of the model. Channels 4 and 5 are assimilated over open oceans only. Over land, ice and snow, the sensitivity of the brightness temperatures to the background skin temperature is computed using RTTOVS-6. If the sensitivity to the skin temperature exceeds a (conservative) empirically determined threshold, then that channel is not assimilated. The reasons for eliminating the channels that see the surface are 1) NOGAPS background skin temperatures over land, ice and snow have large errors, and 2) we have not yet implemented a microwave land surface emissivity model. Including the higher peaking channels over land improves the forecast skill over large land areas such as Europe and Asia.

AMSU-A Channel	Assimilated	N-15 ob error	N-16 ob error	Limited use over land, snow and ice
1	No*	2.13	2.13	Yes
2	No*	2.43	2.43	Yes
3	No*	1.24	1.24	Yes
4	Yes	0.60	0.60	Yes
5	Yes	0.30	0.30	Yes
6	Yes	0.20	0.20	Yes
7	Yes	0.25	0.25	
8	Yes	0.28	0.28	
9	Yes	0.30	0.30	
10	Yes	0.40	0.40	
11	No	Failed	0.40	
12	No	0.49	0.49	
13	No	0.58	0.58	
14	No	Failed	0.95	
15	No*	1.93	1.93	Yes

Table 1. AMSU-A channel usage and nominal observation error standard deviations (K). An * indicates a channel used for quality control.

2.2 *Quality Control Procedures*

The presence of large amounts of cloud liquid water, heavy precipitation or cloud ice all introduce either nonlinearities in the forward radiative transfer model or a scattering signal (rather than emission), which are not handled by the fast radiative transfer model, RTTOVS-6. Over open ocean, several algorithms provided by Grody (NESDIS; personal communication) are used. First, cloud liquid water (CLW) is derived using channels 1 and 2. If the computed CLW exceeds 0.22, channels 1-5 are not assimilated. Similarly, a scattering index is computed using channels 1,2, and 15. If the scattering index exceeds 10, channels 1-6 are not assimilated. Finally, channels 1 and 3 are used to check for sea-ice. If the latitude exceeds 50^{O}, and the computed discriminating function is greater than 0.45, then channels 1-5 are not assimilated.

Another quality control check, modeled on one used at NCEP (Derber, personal communication), is to compute the change in surface emissivity required to fit the innovation (observed minus computed brightness temperatures). AMSU-A channels 1-6 are rejected if this value exceeds 5% for channels 1 and 3, and 3% for channel 2.

The model fields are used to check for mixed fields of view, land, or the presence of sea-ice or snow over land. In these cases, channels 1-6 or 1-5 are rejected, respectively. The final quality control check for all terrain types eliminates any observation where the innovation exceeds three times the expected observation error standard deviation.

2.3 *Background Specification above the Model Top*

The RTTOVS-6 fast radiative transfer model requires that background values of temperature and humidity be specified up to 0.1 hPa. In the present operational implementation, NESDIS ATOVS retrievals are used to provide the temperature information. All NESDIS retrievals within one degree of latitude/longitude of the AMSU-A locations are averaged, and the mean value is used above 4 hPa. A constant value of 0.001 g/kg is used for the background humidity above 4 hPa. If a matching NESDIS retrieval cannot be found, the AMSU-A radiances at that location are not used. This approach is not ideal for an operational implementation, as AMSU-A radiances are available for assimilation several hours before the ATOVS retrievals, due to the additional time required to process and disseminate the retrievals at NESDIS. For the operational real-time run, with a +3 hour data cutoff, anywhere from a few hundred to several thousand more AMSU-A radiance profiles are available for assimilation than ATOVS retrievals. The problem is even more pronounced for the early data cuts. NRL-Monterey is actively pursuing alternative approaches, including pushing the NOGAPS model top up to 0.01 hPa. One approach that is currently being tested is the use of the FNMOC stratospheric analysis. Since the stratospheric analysis uses NESDIS ATOVS retrievals, this does not entirely eliminate the dependence on NESDIS retrievals, but greatly reduces the impact of the late arriving retrievals.

2.4 *Observation Thinning*

Currently we assimilate the AMSU-A microwave radiance data from two satellites, NOAA15 and NOAA16.

The amount of raw radiance data is on the order of 64 MB per day, and will be increasing dramatically in the near future, as new satellites are launched with ever higher resolution instruments. We cannot use all of the data we receive, so we must turn to data thinning or superobbing. Ideally, data thinning and superobbing substantially reduce data volume while retaining all of the useful information. Superobbing has two disadvantages compared to data thinning. It is more computationally expensive to compute a weighted average than it is to select a data point near the center of a grid box, or even a random point in a grid box. More importantly, because we do not know the observational error covariance of microwave radiance data, it is easy to underestimate the observation error of a superob, which may give that observation too much weight compared to the background field. Our method, described below, simultaneously thins the data and removes both exact and approximate duplicate observations.

We define a lat-lon grid such that the area of the grid boxes remains approximately constant (the longitudinal dimension of the grid box increase as the bands approached the poles). The resolution is approximately 100 km^2, roughly half that of the underlying T239 version of NOGAPS. Each radiance observation is then assigned an integer signature, constructed partly from the latitude and longitude, and partly from a user-defined priority number. The priority number can be a function of how close an observation is to the center of the grid box, or to the analysis time, or of which satellite is more reliable, etc. The signature is sorted, and then modified to remove the priority number. All observations in a grid box will now have the same (modified) signature; however, the observations that previously had a numerically smaller signature (i.e. higher priority) will appear first in the list. Finally, we can flag the duplicates by comparing the modified signature list with itself, offset by one. All matches in that comparison are duplicates.

One advantage of this method is that it can handle a large amount of data, because the time complexity is dominated by the parallel merge sort, which is fast (O(n log n)). The post-sort, pre-flag signature modification allows a great deal of flexibility in the selection of data. Of course, by not using a superobbing approach, it may be that we sometimes select a non-representative observation in a grid box, but if is too far off the mark, it will be eliminated by the quality control. Currently we do not use time in the signature, which results in taking the earliest ob that fits into the grid box, rather than the one closest to the analysis time, which should be superior. This will be changed in the near term.

2.5 *Bias Correction*

There are systematic differences between observed radiances, and those simulated using any NWP model (e.g. NOGAPS) along with a fast radiative transfer (RT) model (e.g. RTTOV-6). This bias in the innovations (observed minus background) can be larger than the signal, and must be reduced before NAVDAS can successfully assimilate them. These differences are due to the instrument itself (e.g. the scan bias), errors of representativeness of the NWP model, errors in the RT model (collectively denoted air-mass bias, which is a function of the underlying atmosphere), and any data pre-processing. After the success of the simple regression scheme developed by Eyre (1992), most major weather centers adopted some form of linear regression to correct for radiance bias. The NRL method is a modified version of the approach described by Harris and Kelly (1999), with some changes suggested by John Derber of NCEP.

We perform the bias correction in two steps, based on fifteen days of innovation statistics (observed radiances minus background). A simple, global scan-bias correction sets the mean innovation at each scan angle to be equal to the mean innovation at the center scan angle. Then a global linear regression of the scan-corrected innovations against seven predictors corrects the air-mass bias. Six of the predictors are model fields (surface skin temperature, total column precipitable water, and 1000-300 and 200-50 hPa thicknesses (weighted by the sine squared and cosine squared of latitude)), and are similar to the Harris and Kelly predictors. The seventh predictor is based on the cloud liquid water formula of Grody (NESDIS; personal communication), and is a function of radiances in channels 1 and 2 of AMSU-A. This seventh predictor is helpful in correcting bias in channels 4 and 5 of AMSU-A. Bias maps comparing the reduction in spatial root mean square (rms) error of the innovations show a small advantage of the NRL method over Harris and Kelly, most notably in channel 4 (Fig. 1). Merely looking at a static bias map, however, does not tell us that the NRL method will produce better forecasts; assimilation runs in a cycling system are be necessary for that. Results of assimilation tests comparing the two methods, as well as a hybrid method developed at NRL, will be presented at the 13th Satellite Conference.

2.6 *Automated Bias Corrections for Operations*

For research runs, typically we already have a reasonable set of initial bias coefficients from a previous run, and set of innovation statistics for the fifteen days before the start date. If we do not have either of those, then we run for approximately ten model days assimilating NESDIS retrievals in order to generate statistics to create an initial set of bias coefficients. We then switch to radiance assimilation and continue the run. For the initial research and development of the radiance assimilation, we updated the bias coefficients manually by monitoring the bias corrections with simple statistics, plots, and maps. The need to update the bias coefficients was determined subjectively, and was usually based on the residual bias and rms error of the assimilated innovations. New coefficients were generated using the most recent two weeks of innovations, and implemented. For research purposes, this procedure is sufficient, but it is less than ideal for operations, or for general assimilation tests.

Operational jobs at FNMOC consist of UNIX scripts that call parallelized Fortran code, run in a batch queue environment on a 512-processor machine. For operational use, we want to minimize human intervention. We therefore need an automated warning system that tells us when human intervention is necessary. We also want to keep an archive of bias correction coefficients, both as a record of what was actually used, and as starting coefficients for historical runs and reanalyses. Much of the monitoring, automated warning system, and coefficient archiving can be done at the UNIX script level, with some small modifications to the Fortran code.

For both research and operational runs, we routinely calculate the bias correction coefficients for the last fifteen days of data every six hours, so it seems natural to use the most up to date information immediately, rather than waiting two weeks or a month to evaluate whether the coefficients should be updated. If fifteen days of data are not available, the bias coefficients will stay fixed until enough data for a reliable bias coefficient update is available, and then the coefficients will be updated every six hours. This also simplifies the archiving aspect, as we now have a small file of coefficients four times per day, every day, which we can date stamp, save, and use in the future. It is still possible, however, that even with continuous updating, the bias corrections may not be performing well. Simple thresholds for bias and rms error in each AMSU-A channel are stored in a flat file. The Fortran code compares bias and rms error values with the expected maximum values, and writes small text files indicating when maxima were exceeded. The UNIX scripts then check for the existence of these files, and create email messages summarizing their contents, which are then mailed to whomever is on the appropriate mailing list. We can also optionally send routine emails each time the coefficients are updated and no problems are detected. Email can be checked quickly on weekends or in the evening, allowing for a quick evaluation of and a timely response to emergencies, without the need to access the graphical monitoring system, which can be cumbersome with slow telephone connections. The lack of a routine email can also serve a useful purpose, showing that the bias update job did not run. The dynamic updating system described above has been used since the first day of operational radiance assimilation, and has been quite successful, requiring very little human intervention. This approach has also become the preferred mode for research assimilation experiments.

3. DATA ASSIMILATION / MEDIUM-RANGE FORECAST TESTS

The impacts of the AMSU-A assimilation described in Section 2 were examined using data assimilation/forecast intercomparisons with both control runs and the operational runs. The operational run (NAVDAS 1.0 in the subsequent figures) was the T239L30 NOGAPS (Hogan et al. 1991) with the operational NAVDAS analysis (Daley and Barker, 2001; Goerss et al., 2003), and assimilated NESDIS ATOVS retrievals. The AMSU-A radiance assimilation configuration (NAVDAS 1.1 or AMSU-A in the subsequent figures) included the changes described in Section 2. The control runs used the same versions of NAVDAS, NOGAPS and the same observational data as the radiance assimilation runs, but assimilated ATOVS retrievals instead of AMSU-A radiances. The data assimilation portion of the tests were run in a mode similar to the operational the data assimilation run -- a six-hour assimilation cycle (data quality control, tropical cyclone bogusing, wind, temperature, and moisture analysis, sea-surface temperature and sea-ice concentrations from U.S. Navy analyses, and snow amounts from the US Air Force analysis). However, unlike operations where six-day forecasts are run every six-hours, a five-day (120 h) forecasts was run once a day from the 00 UTC initial conditions. In additional, the operational run benefits from a post-time analysis; i.e., an analysis with a late data cut of around +8:00 hrs that is used to provide the 3, 6 and 9-hr forecasts that serve as the background for the next assimilation cycle. The post-time run gives a slight but noticeable improvement to the forecast skill.

Standard statistical scores, including mean errors, root mean square errors, anomaly correlations (AC), tropical cyclone (TC) tracks, and comparisons with radiosondes and surface data were computed for each 120-hour integration. The test periods correspond to a NH summer/SH winter (July 15 – Sept. 30 2003) and a spring transition season period (April/May 2004).

The comparisons for the NH summer, which are shown in Figs 2 – 14, are with a control NAVDAS/NOGAPS run that assimilated NESDIS ATOVS retrievals. The 500 hPa height AC for the SH (80S-20S) and NH (20N - 80N) for the July 15 to September 30, 2003, are given in Figs. 2 and 3, respectively. They demonstrate a significant positive impact at all forecast lengths for both hemispheres, especially the SH (winter). The forecasts are improvements in the SH are at least 12 hrs for all forecast lengths beyond 24 hrs. At 1000 hPa the SH (Fig. 4) and NH (Fig. 5) heights show similar improvements over the control run. In the Tropics (20S – 20N), the vector rms wind error is often used as an indicator of skill in place of the AC. It can be seen that at 850 hPa there is no change in the error with radiance assimilation (Fig. 6). At 250 hPa there is a slight degradation in the upper level tropical winds early in the forecast period, but the differences are not statistically significant (Fig. 7). Overall, the rms error in the lower tropical winds is deemed acceptable, considering the positive results in the other statistics.

Figures 8 - 11 are the comparisons of the AMSU-A assimilation run with the ATOVS retrieval assimilation run using the radiosonde data for verification. Both winds and temperature show reduced errors for all forecast times with respect to the radiosonde data with AMSU-A radiance assimilation.

Figures 12 and 13 show the SH and NH 500 hPa height anomaly correlation for the 96-hr forecasts for the summer 2003 case. Overall, assimilation of AMSU-A radiances reduces the number of forecast “busts”.

Figures 14 – 17 are the corresponding figures for the spring 2004 comparison of the pre-operational AMSU-A assimilation beta runs at FNMOC (NAVDAS 1.1) versus the operational NAVDAS run using NESDIS ATOVS retrievals (NAVDAS 1.0). Both jobs are run at nearly the same time so that the data counts are essentially the same. The assimilation and forecast systems were also the same, but for the difference of radiances vs.

retrievals. The overall results are comparable to those found for the summer 2003 runs. The mid-troposphere skill in both hemispheres as measured by the 500 hPa AC is even greater for the spring season (Figs. 14 and 15), as were the SH and NH 1000 hPa height forecasts (Figs. 16 and 17). The tropical cycle tracks forecasts, radiosonde verifications, and tropical wind verification results were the same or better than those shown for the summer 2003 case.

Accurate tropical cyclone track forecasts are of great importance to U.S. Navy and civilian interests. Overall, assimilation of AMSU-A radiances improves the prediction of tropical cyclone tracks and intensity. A summary of NOGAPS tropical cyclone track prediction, as verified against the Joint Typhoon Warning Center "best track" positions for September 2003 is shown in Figure 18. AMSU-A assimilation shows an advantage at all forecast times from one to five days. (The numbers below the forecast time are the total number of forecast tracks for the month used in the comparison.) The results over all three basins (Western Pacific, Eastern Pacific, and Atlantic) are statistically significant at between 75% (2-day forecast) and 98% (3-day forecast) confidence levels.

In addition to the boreal summer 2003 and spring 2004 runs described above, the AMSU-A radiance assimilation was run in near real time from mid-October 2003 through June 2004. These results are not presented here, principally because the comparisons with the operational NOGAPS systems are not as clean. However, the forecast improvements were similar to, and for some time periods superior to, those presented here.

4. SUMMARY AND FUTURE PLANS

The results presented in the paper demonstrate that the radiance assimilation with NAVDAS for NOGAPS is working very well. Improvements in the near future include increasing the use of radiances over land by implementing microwave surface emissivity model and emissivity retrievals, improving the bias correction method, and pushing the model top higher. We will also implement AMSU-A radiance assimilation into the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS™)[1]. We anticipate that AMSU-B 1dvar water vapor retrieval assimilation will become operational this fall for NOGAPS, as will radiance assimilation of the higher-peaking HIRS/3 channels.

In conclusion, the development of NAVDAS has paved the way to effectively utilize the vast amounts of satellite data that will be available over the next decade with the NPOESS NPP satellites and the European METOP satellites, and eventually NPOESS.

5. ACKNOWLEDGEMENTS

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[1] COAMPS is a trademark of the Naval Research Laboratory

6. FIGURES

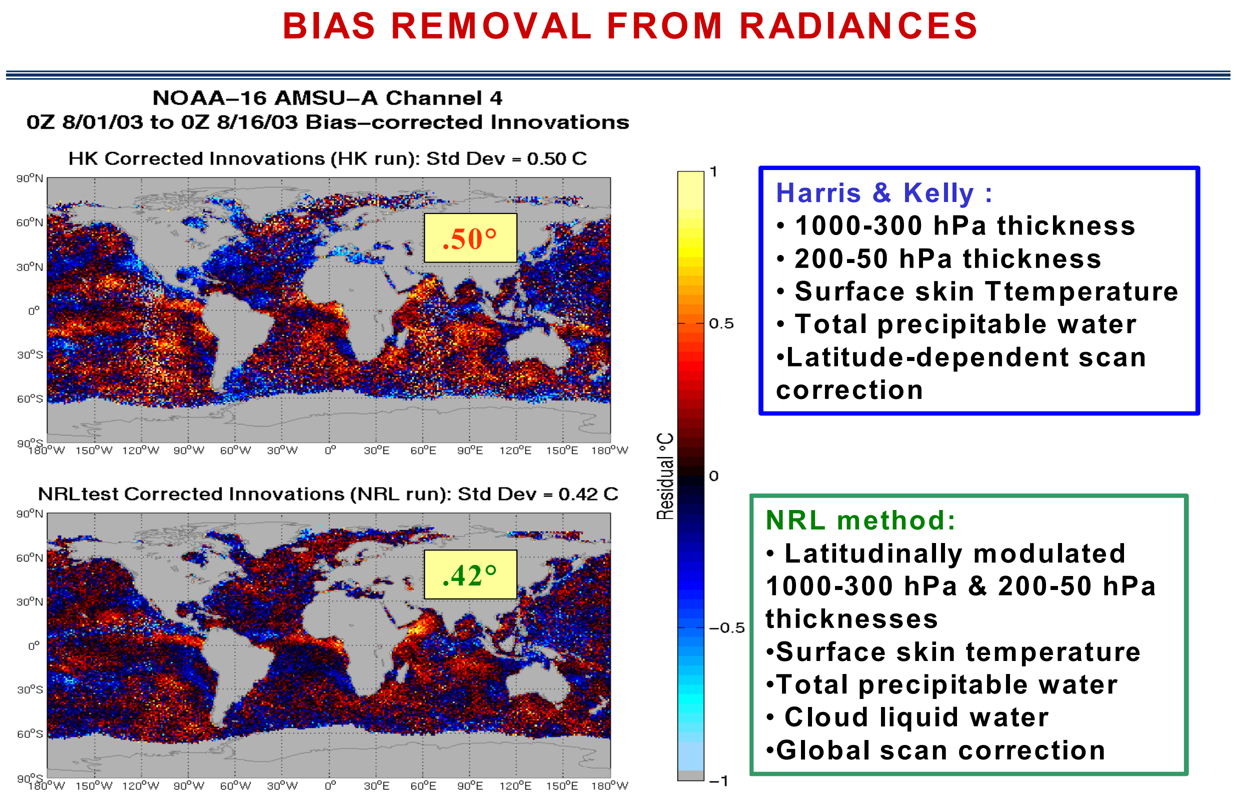

FIG. 1. The reduction in amplitude of the spatial patterns of 15-day innovation bias is greater for the NRL method than for HK.

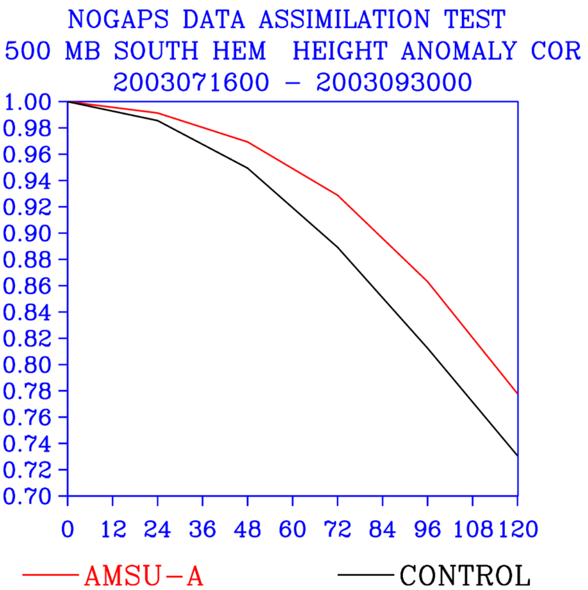

FIG. 2. Southern Hemisphere 500 hPa height AC vs. forecast hour for the summer 2003 case. The test run (AMSU-A) includes NAVDAS assimilation of AMSU-A radiances as described in Section 2. The control run assimilated NESDIS ATOVS retrievals with NAVDAS.

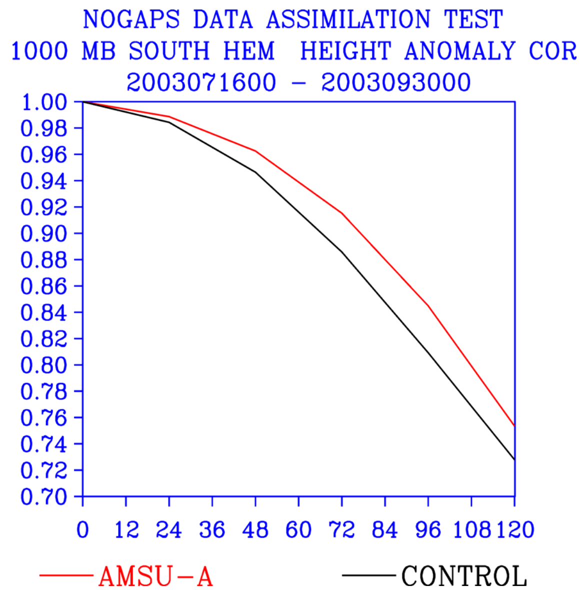

FIG. 4. Same as FIG. 2. for 1000 hPa height.

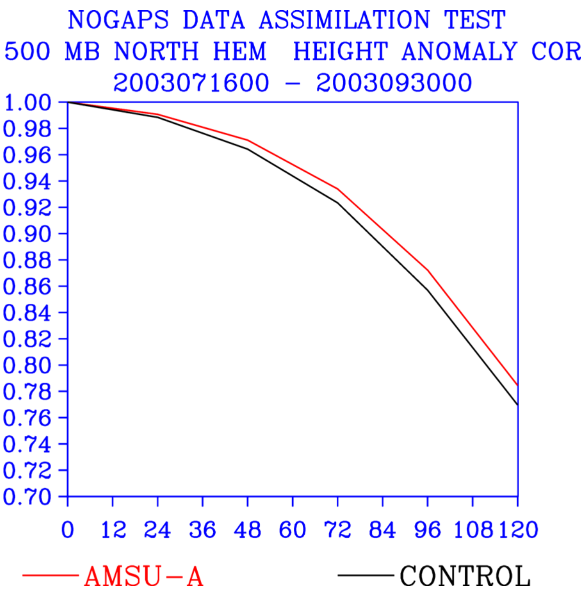

FIG. 3. Same as FIG. 2. for Northern Hemisphere.

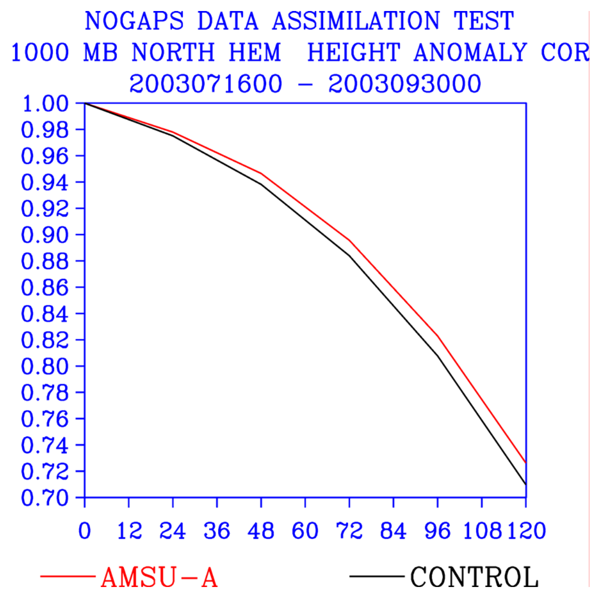

FIG. 5. Same as FIG. 3. for 1000 hPa height.

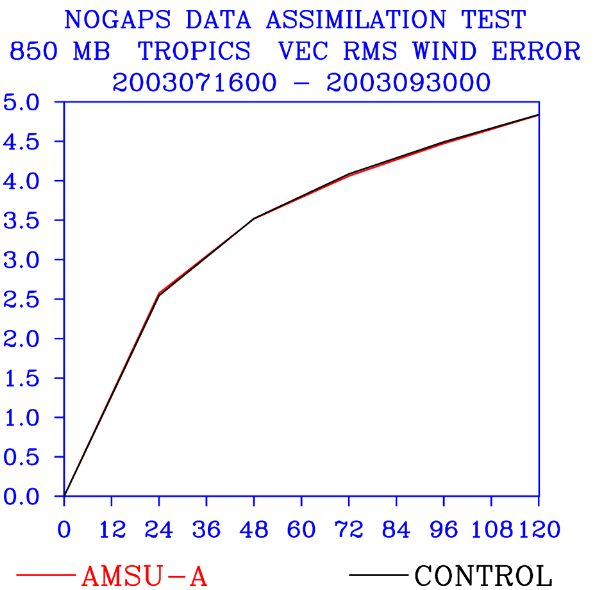

FIG. 6. Tropical 850 hPa vector rms wind error vs. forecast hour for the summer 2003 case. The test run (AMSU-A) includes NAVDAS assimilation of AMSU-A radiances as described in Section 2. The control run assimilated NESDIS ATOVS retrievals with NAVDAS.

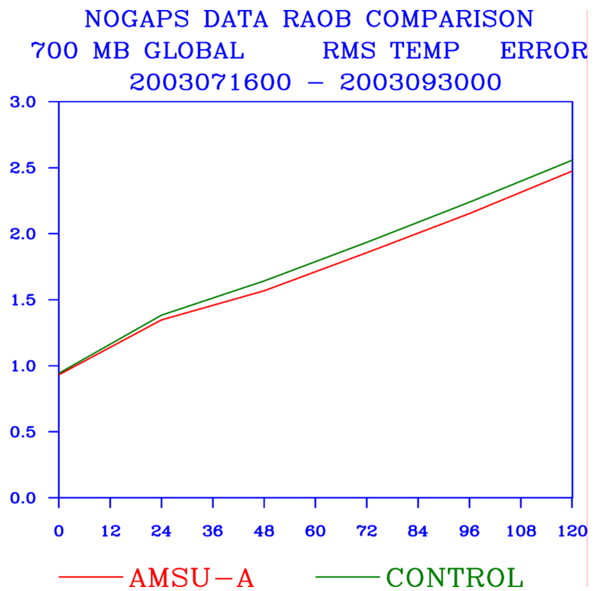

FIG. 8. The 700 hPa temperature rms error with respect to radiosonde vs. forecast hour for the summer 2003 case. The test run (AMSU-A) includes NAVDAS assimilation of AMSU-A radiances as described in Section 2. The control run assimilated NESDIS ATOVS retrievals with NAVDAS.

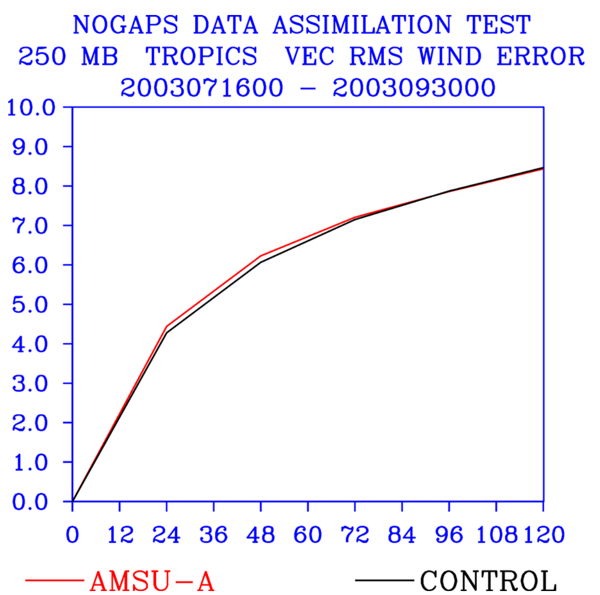

FIG. 7. Same as FIG. 6. for 250 hPa.

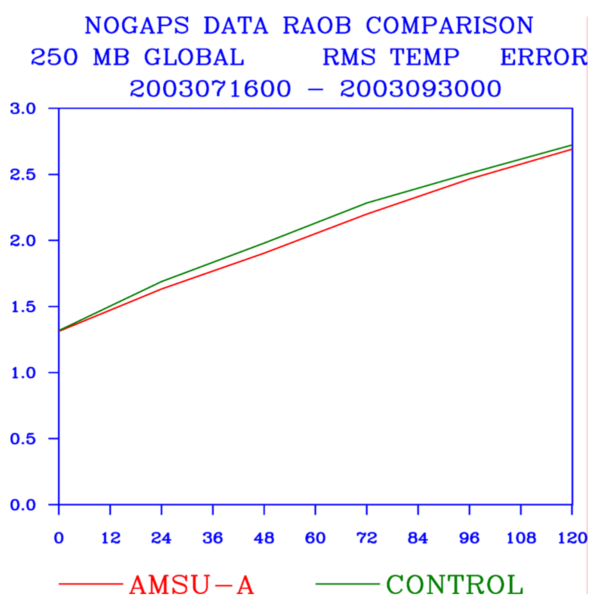

FIG. 9. Same as FIG. 8. for 250 hPa.

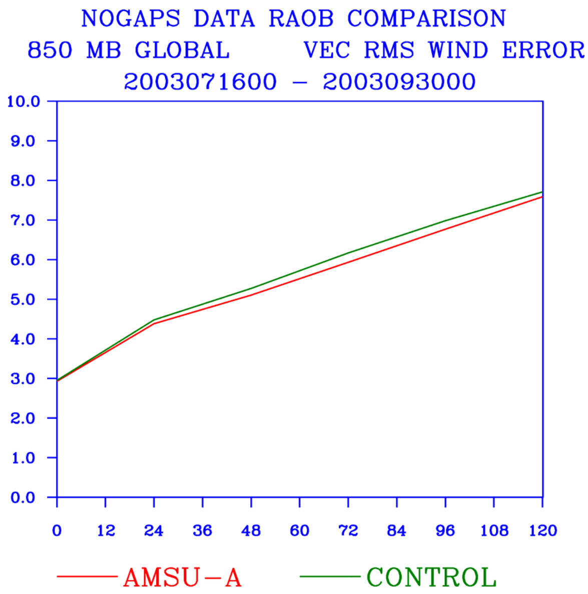

FIG. 10. The 850 hPa vector rms error with respect to radiosonde vs. forecast hour for the summer 2003 case. The test run (AMSU-A) includes NAVDAS assimilation of AMSU-A radiances as described in Section 2. The control run assimilated NESDIS ATOVS retrievals with NAVDAS.

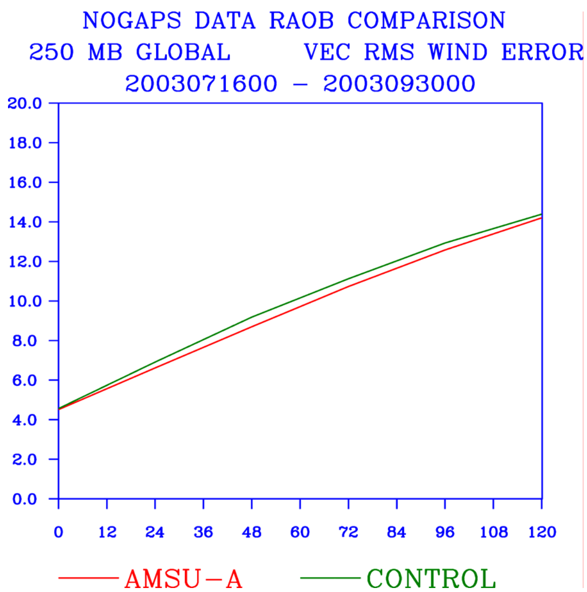

FIG. 11. Same as FIG. 10. for 250 hPa.

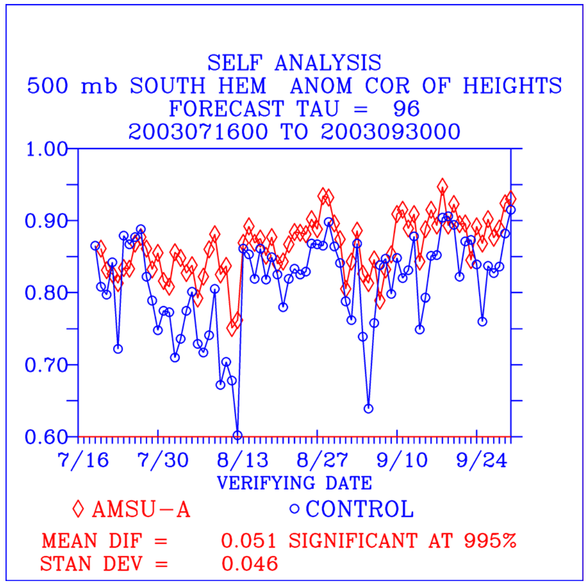

FIG. 12. Southern Hemisphere 500 hPa height AC for the 96-hr forecasts for the summer 2003 case. The test run (AMSU-A) includes NAVDAS assimilation of AMSU-A radiances as described in Section 2. The control run assimilated NESDIS ATOVS retrievals with NAVDAS.

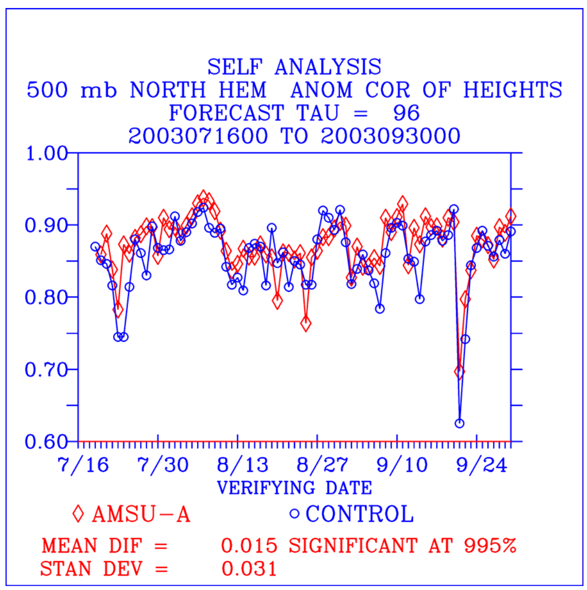

FIG. 13. Same as FIG. 12. for the Northern Hemisphere.

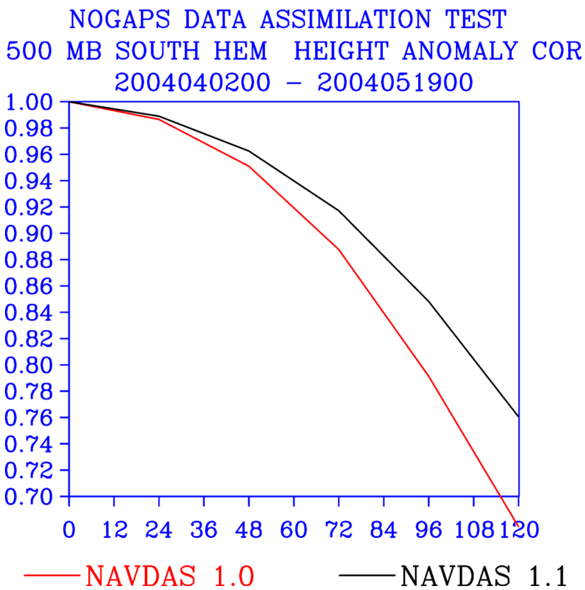

FIG. 14. Southern Hemisphere 500 hPa height AC vs. forecast hour for the April/May 2004 pre-operational test period. NAVDAS 1.1 includes AMSU-A radiances, while NAVDAS 1.0 used NESDIS ATOVS retrievals.

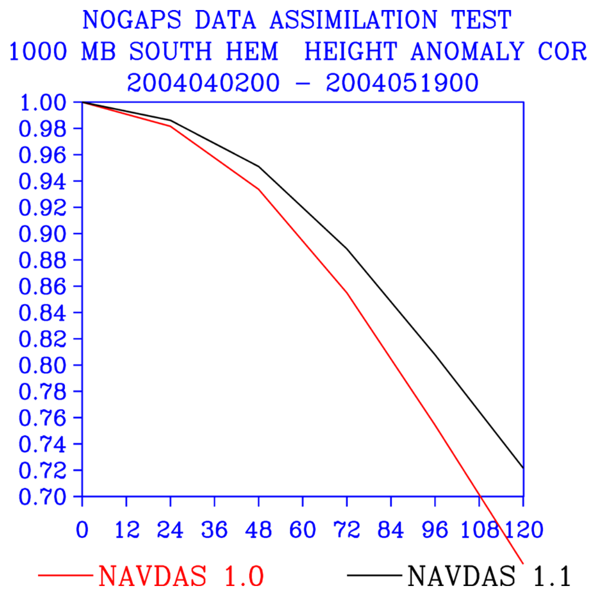

FIG. 16. Same as FIG. 14. for 1000 hPa height.

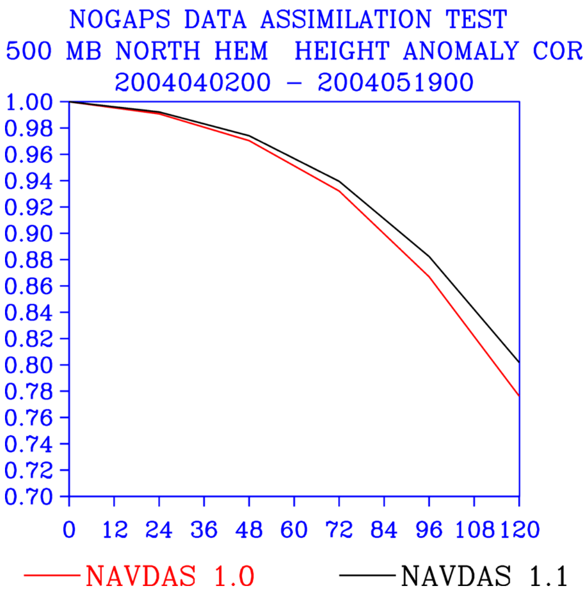

FIG. 15. Same as FIG. 14. for the Northern Hemisphere.

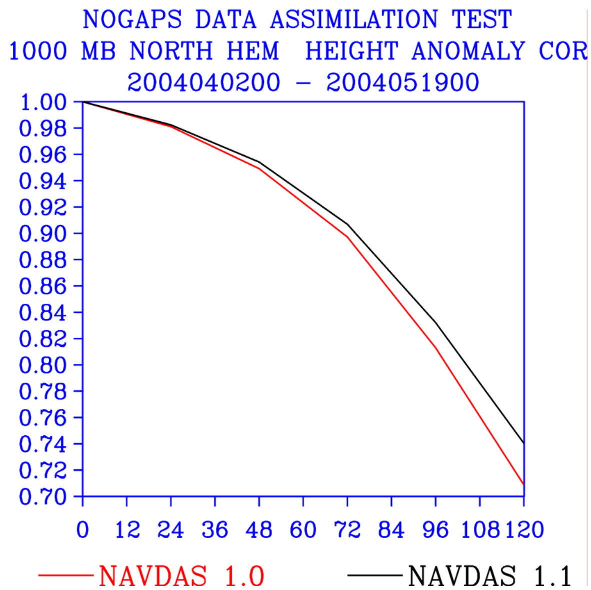

FIG. 17. Same as FIG. 16. for the Northern Hemisphere.

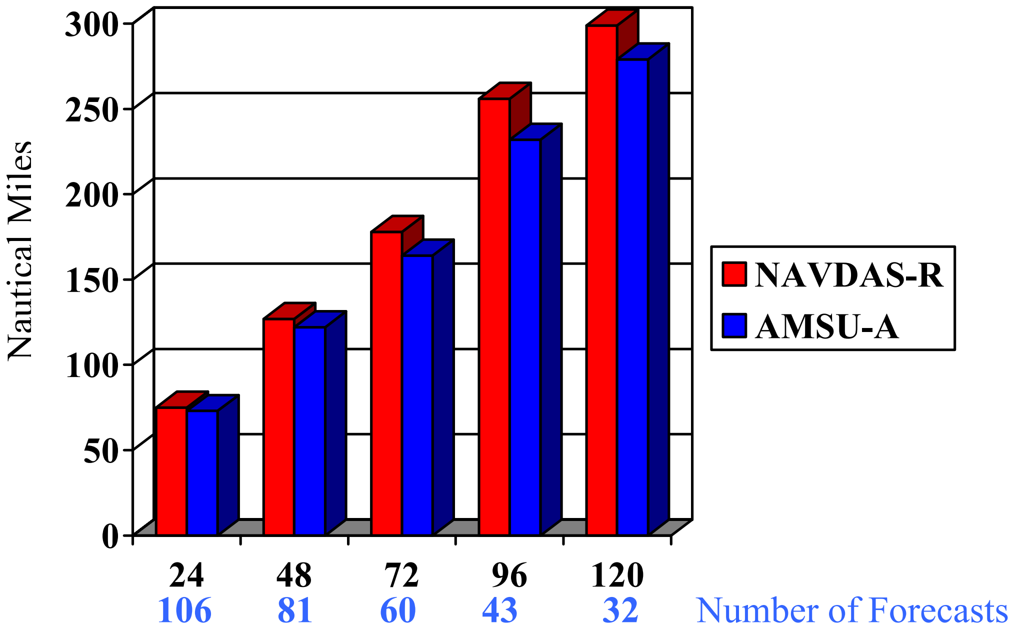

FIG. 18. A comparison of the mean tropical cyclone track error vs. forecast hour for the month of September 2003. The numbers below the forecast time are the total number of forecast tracks for the month used in the comparison. The test run (AMSU-A) includes NAVDAS assimilation of AMSU-A radiances as described in Section 2. The control run (NAVDAS-R) assimilated NESDIS ATOVS retrievals with NAVDAS.

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