P3.12 ASSIMILATION OF AMSU-B HUMIDITY PROFILE RETRIEVALS USING THE NRL ATMOSPHERIC VARIATIONAL DATA ASSIMILATION SYSTEM (NAVDAS)

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1. INTRODUCTION

1-D variational retrievals of humidity profiles are calculated from Advanced Microwave Sounding Unit-B (AMSU-B) observations and a NOGAPS (Navy Operational Global Atmospheric Predication System) background. The retrieved humidity profiles are assimilated into NOGAPS using the NAVDAS (NRL Atmospheric Variational Data Assimilation System) 3DVAR system.

The water vapor retrieval was validated by comparing 6.7 μm T_B's (brightness temperatures) from the GOES imager's infrared water vapor channel to forward modeled T_B's generated from the retrieved water vapor profiles. Synthetic and observed T_B's agreed quite well, with a rms error of 3.7 K and a correlation of 0.90.

Results from AMSU-B data assimilation experiments are presented. The AMSU-B model run has a drier middle and upper troposphere, with stronger humidity gradients. The impact of AMSU-B data on 500-mb height anomaly correlation scores is small. Results from tropical cyclone verification are positive, with improved position and intensity forecast from the AMSU-B run.

2. BACKGROUND

NAVDAS (Daley and Barker, 2001) is a three-dimensional variational analysis system cast in observation space. The set of equations are

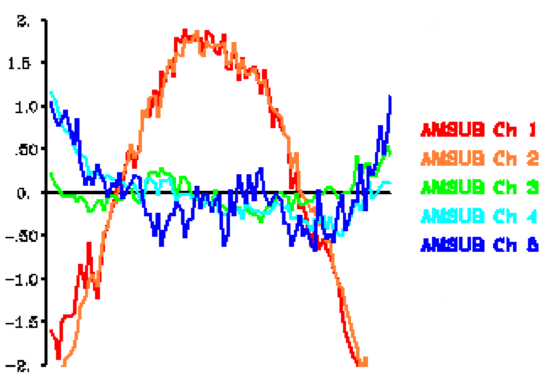

Figure 1. Scan bias (K) as a function of beam position for the *NOAA-16* AMSU-B for 19 May 2003.

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preconditioned using dual block diagonal preconditioners, and the conjugate gradient method is used to minimize the pre-conditioned cost function. Vertical eigenvector decomposition of the background error covariance matrix leads to great generality in formulating nonseparable error covariances as well as enormous efficiencies in handling vertical profile and sounding observations. Forward operators are formulated and used for the direct assimilation of satellite radiances, special sensor microwave/imager (SSM/I) wind speeds, and total precipitable water. The analysis has been running operationally at Fleet Numerical Meteorology Oceanography Center since October 2003, and with AMSU-A radiances since June 2004.

3. AMSU-B HUMIDITY PROFILE RETRIEVALS

The AMSU-B is a microwave radiometer aboard NOAA polar orbiting satellites *N-15*, *N-16*, and *N-17* which measures brightness temperatures at 89; 150; and 183.31 ± 1, 3, and 7 GHz. Observed radiances at these frequencies are sensitive to the vertical distribution of water vapor in the troposphere. Therefore, AMSU-B observations can be used in a water vapor profile retrieval.

3.1 Retrieval Method

The retrieval algorithm is a physical optimal estimation inversion of the observed brightness temperatures constrained by the NOGAPS background (6-hour forecast); this is equivalent to a one-dimensional variational assimilation (1DVAR) of radiances at each observation point. This algorithm is based on the one described in Blankenship et al. (2000) and incorporates the solution to the inverse problem given by Rodgers (2000).

As a precursor to the retrieval, scan biases are removed. A bias (observation minus model) at each beam position is calculated from a dataset of two weeks or longer. These are adjusted so the mean bias is zero, and only the scan-dependent portion remains. This gives corrections for each channel as a function of beam position only, which are applied to the observations. This removes any hardware-dependent scan biases (as well as a possible radiative transfer component). In view of the discrepancies between the model and retrieval climatologies of humidity, no air-mass dependent bias correction is done. This would have the effect of forcing the model climatology onto the satellite observations, when we would rather have the observations influence the model. We recognize that there are biases in the radiative transfer model and retrieval algorithm that should ideally be corrected, but these are small relative to the biases in the NOGAPS model's upper tropospheric humidity. A typical scan bias for all five channels is shown in Figure 1.

The humidity profile retrieval algorithm uses background values of temperature profile, sea surface temperature, and surface wind speed from the NOGAPS forecast. These parameters are held fixed within the retrieval. The forecast also provides the first guess humidity profile. Clouds are turned off in this version of the retrieval.

Forward modeling of 89 GHz brightness temperatures gives poor comparisons with NOGAPS, so only AMSU-B observations from the four higher frequency channels (183±1, 3, 7; and 150 GHz) are used. The information loss from this is minimal since the sensitivity functions of the 89 and 150 GHz channels are quite similar. Possible contributors to the 89 GHz modeling error include uncertainties in surface emissivity calculation, the larger footprint size, and instrument bias.

The algorithm tries to minimize the cost function

$$J(x) = (\mathbf{y} - \mathbf{H}(\mathbf{x}))^T \mathbf{S}_{\boldsymbol{\varepsilon}}^{-1} (\mathbf{y} - \mathbf{H}(\mathbf{x})) + (\mathbf{x} - \mathbf{x_b})^T \mathbf{S_a}^{-1} (\mathbf{x} - \mathbf{x_b})$$

where **y** is the vector of observations (brightness temperatures), **H** is the forward model, $\mathbf{S}_{\boldsymbol{\varepsilon}}$ is the observed plus forward model error covariance matrix, **x** is the atmospheric state vector (humidity profile), $\mathbf{x_b}$ is the background state, and $\mathbf{S_a}$ is the background error covariance matrix. This is equivalent to maximizing the Bayesian probability of atmospheric state **x** given knowledge of $\mathbf{x_b}$, **y,** and their error characteristics. We solve for a new **x** which minimizes this function using a linearization of **H**(**x**) about the current **x**. This process is repeated until convergence is obtained. If the retrieval fails to converge within 12 iterations it is rejected, but most converge in 3 to 6 iterations

The retrieval algorithm returns the logarithm of specific humidity (ln Q) at the 26 NOGAPS pressure levels from 1013 to 122 hPa. (The retrievals give little information in the stratosphere.) The retrieval error at each level is calculated from the specified background errors (NOGAPS forecast errors) and the observed plus forward (O+F) model brightness temperature errors.

3.2 Retrieval Results

The mean difference in ln Q between retrieved and model moisture fields as a function of pressure is shown in Figure 2. Relative to the retrievals, the model is too dry above 700 mb and slightly too moist at lower levels. Here we present a validation of the retrievals by intercomparison with infrared observations from GOES. We note that, prior to AMSU-B assimilation, NOGAPS assimilated few upper-tropospheric water vapor measurements (limited to radiosondes and aircraft observations), so we do not expect its moisture field in the upper troposphere to be extremely accurate.

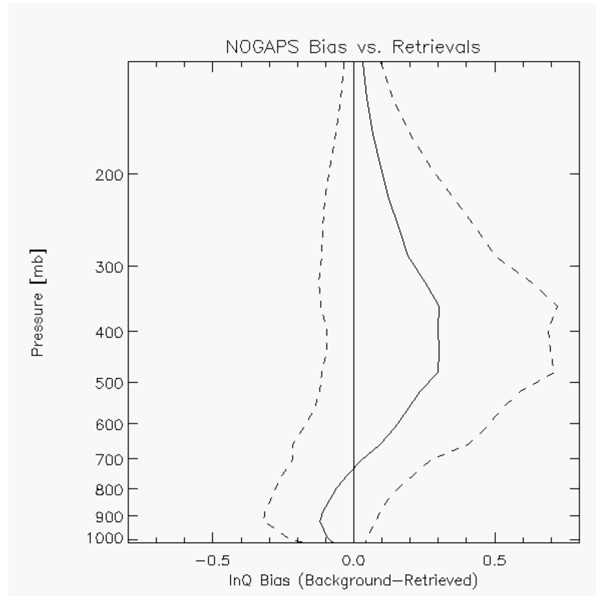


Figure 2. Mean difference in ln(specific humidity), Dashed lines show the difference plus or minus one standard deviation.

Further validation of the retrieval method (versus radiosondes and ECMWF analyses) can be found in Blankenship et al. (2000).

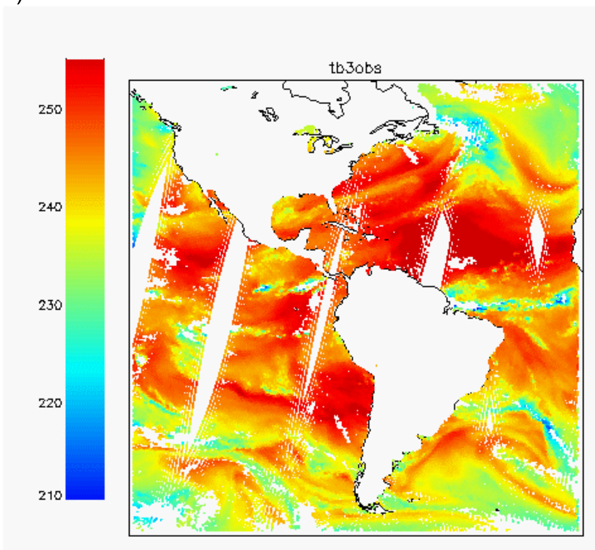
3.3 Validation of Retrievals with GOES Observations

As a validation of the water vapor profile retrievals, GOES water vapor channel observations at 6.7 µm were compared with simulated observations. The 6.7-µm band is also sensitive to water vapor in the upper troposphere. The observation time of the GOES data was 14:45 UTC on 12 Mar 2004. The simulated GOES T_B's were calculated from a retrieved atmosphere using the RTTOV-7 forward model. The retrieval was based on AMSU-B data within 3 hours of 15:00 UTC, with a first guess humidity field and fixed temperature field from a NOGAPS 3-hour forecast. (In the assimilation cycle, analyses rather than 3-hour forecasts are used, but in this case the forecast was used to match the 14:45 UTC time of the available data.) To eliminate problems with unrealistic stratospheric humidity in this version of NOGAPS, humidity at levels above 122 mb was set to the RTTOV-7 minimum value.

Figure 3 shows the observed GOES T_B's (at AMSU-B locations) as well as those simulated from the retrievals. The field is reproduced quite well. The largest discrepancy is due to some clouds in the ITCZ that affect the observations (and were not included in the forward model), but the area affected is relatively small.

Table 1 gives quantitative results from this experiment. The values obtained by using the NOGAPS background rather than retrievals are also given. There is a significant improvement in all measures.

a)



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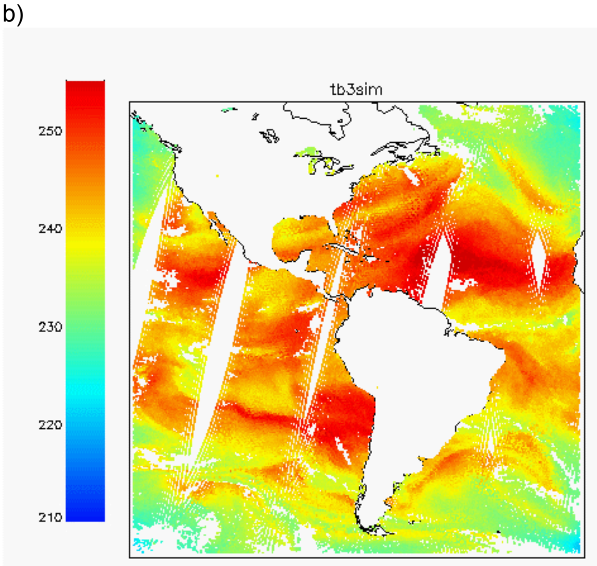


Figure 3. a) Observed GOES-E 6.7 µm brightness temperatures for 12 Mar 2004 at 14:45 UTC. b) Simulated 6.7 µm brightness temperatures at 15:00 UTC.

	Background	Retrievals
Bias	-10.7 K	-1.79 K
Standard Deviation	6.32 K	3.27 K
RMS Error	13.9 K	3.72 K
Correlation Coefficient	0.50	0.90

Table 1. Statistics for simulated TB's (from NOGAPS background and from retrievals) relative to GOES-E observed TB's.

These results show that the NOGAPS (without AMSU-B) middle- and upper-tropospheric moisture fields are incompatible with radiometric measurements from both microwave and infrared instruments, while the satellite methods are in good agreement. The large reduction in the bias for retrievals is due to the NOGAPS model's overestimate of humidity, which was noted earlier. The high correlation is evidence that the retrieved water vapor is properly distributed.

4. USE OF AMSU-B IN NAVDAS

Satellite moisture profiling information is incorporated via the assimilation of retrievals rather than radiances as a first step because NAVDAS needs special code to handle a nonlinear operator. Unless a costly outer loop is added to the NAVDAS solver, the program assumes that the Jacobian matrix of changes in observations with respect to changes in model variables is constant. Since this assumption is not valid for radiometric observations of water vapor, we let the 1DVAR retrieval handle the nonlinearities inherent in a water vapor profile retrieval so all observations input to the 3DVAR system (NAVDAS) are linearly related to model quantities.

Initially all AMSU-B observations within 3 hours of the analysis time from NOAA-16 and NOAA-17 are read in. NOAA-15 is not used due a noisy channel 4 (183.31±3 GHz, perhaps related to an incomplete radio frequency interference correction). The AMSU-B data are thinned to approximately 1 degree latitude by 2 degrees longitude in the tropics, and to an equivalent density elsewhere. Data over land, coast, and sea ice are screened out, as are data which fail gross temperature checks. Points with a high scattering index-- computed from 89 and 150 GHz measurements and indicative of significant cloud (Greenwald and Christopher, 2002)—and retrievals which fail to converge (possibly due to heavy cloud or precipitation in the scene or poor initial conditions) are also rejected. After these checks, there are approximately 9,000 water vapor retrievals from AMSU-B per update cycle ready to be assimilated. These are output to NAVDAS as relative humidity observations at (up to) 9 layers from 1005 to 122 mb, together with the computed uncertainties.

Retrievals are assimilated into the NOGAPS forecast model using the NAVDAS software. These data are assimilated simultaneously with many other data types including radiosondes, surface observations, satellite winds, and NESDIS temperature retrievals from HIRS (High Resolution Infrared Sounder) and AMSU-A. NAVDAS is run on a 6-hour cycle at 00, 06, 12, and 18 UTC. All observations within ±3 hours of the analysis times are used along with the 6-hour forecast from the last update to produce a new analysis, which is then used as the starting condition for the next NOGAPS forecast.

5. RESULTS

The impact of AMSU-B data on NAVDAS was tested by performing two forecast runs: a control run and a run assimilating AMSU-B water vapor profile retrievals. These results are from a model run for August and September of 2003 at a model resolution of T239 with 30 vertical levels.

5.1 Impact on Fields

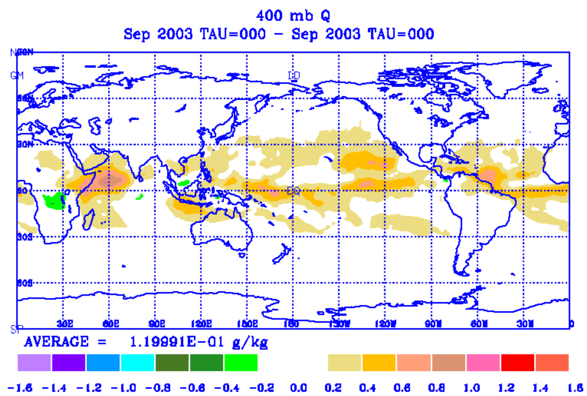


Figure 4. 400-mb monthly mean specific humidity difference for September 2003, control minus AMSU-B.

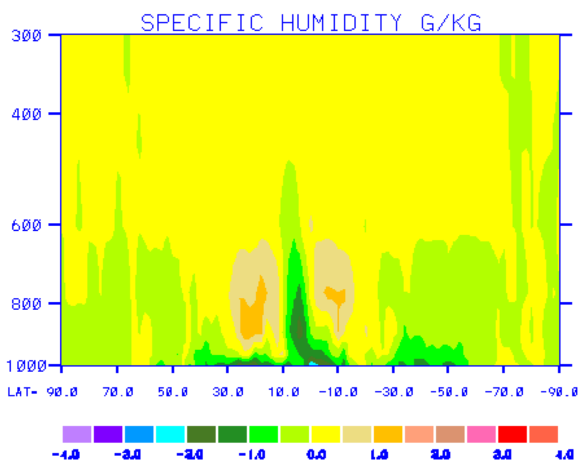


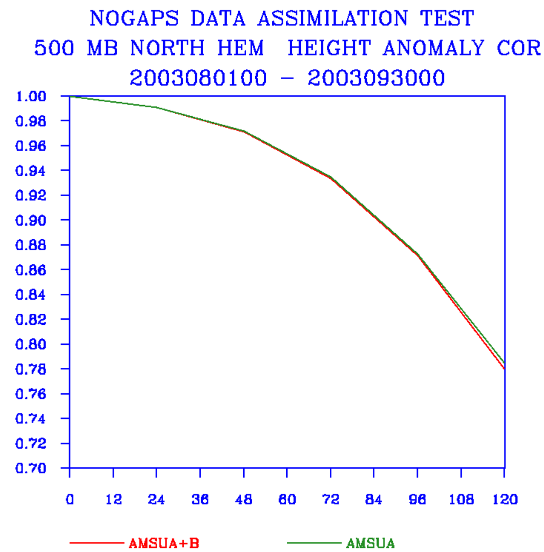
Figure 5. Zonal monthly mean specific humidity difference for September 2003, control minus AMSU-B.

Changes to the NOGAPS moisture fields due to the assimilation of AMSU-B data are generally in line with expectations. Figure 4 shows the specific humidity difference at 400 mb. The AMSU-B run is generally drier at this level as the model adjusts toward the retrieved humidities. Overall, we see a moistening at low levels and a drying in the middle and upper troposphere.

Not surprisingly, details of the water vapor distribution also change with the addition of AMSU-B data. Figure 5 shows the zonal mean cross-sectional change in specific humidity. We see that the ITCZ is moistened and that drying occurs in the subtropical highs (except very near the surface). In general, the addition of AMSU-B observations strengthens model moisture gradients, counteracting a model tendency to smooth out moisture. Further results from earlier runs may be found in Blankenship and Baker (2003).

5.2 Anomaly Correlation Scores

a)



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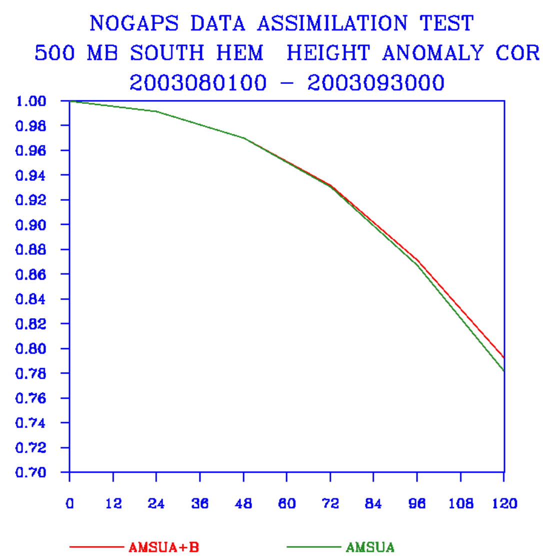
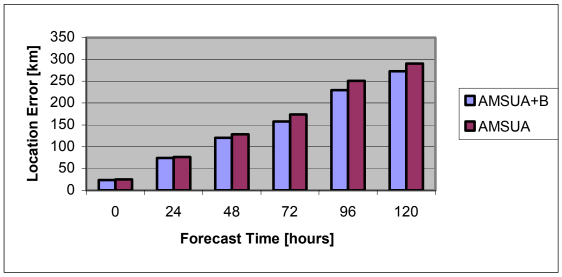


Figure 6. 500-mb height anomaly correlations for the AMSU-B run (red) and control run (green). a) Northern Hemisphere, b) Southern Hemisphere.

A common diagnostic for assimilation runs is the 500-mb height anomaly correlation. Results from the two runs are presented in Figure 6. The impact is slightly negative in the Northern Hemisphere and slightly positive in the Southern Hemisphere. The moisture field is only indirectly related to the height fields, so we would expect the impact to be small. In fact, it is encouraging that the scores remain approximately the same while the model climatology changes, since the NAVDAS analysis is now fitting to more data.

5.3 Tropical Cyclone Verification

a)



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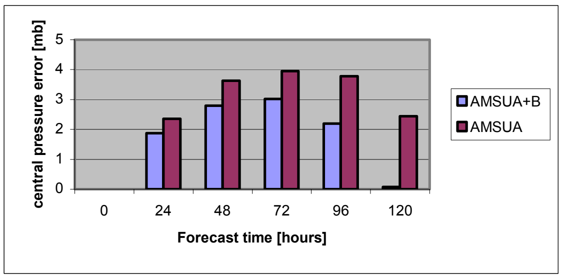

Figure 7. a) Location error for the AMSU-B run ("AMSUA+B") and control run ("AMSUA"). b) Central pressure error.

Forecasts of tropical cyclone position (as defined by lowest sea level pressure) and central pressure from all storms tracked during the two months for both runs were validated against the best tracks as reported by the Joint Typhoon Warning Center and the National Hurricane Center. The number of forecasts varied from 106 at 24 hours to 32 at 120 hours. The AMSU-B run gave consistently better results for both position and central pressure, as shown in Figure 7. Position error was reduced by an average of 6.9% for 24- to 120-hour forecasts and central pressure error was reduced by 1.24 mb, on average.

6. FUTURE PLANS

Possible modifications to the retrieval include use over land (only using upper-tropospheric channels and defaulting to the model humidity for lower levels) and switching on the cloud retrieval. Changes to NAVDAS could include better specification of background humidity errors and use of cloud information from the humidity retrieval.

Transition of AMSU-B retrieval assimilation to the operational version of NAVDAS and NOGAPS at the Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC) is targeted for the fall of 2004. We also plan to move to direct assimilation of AMSU-B radiances (as opposed to retrievals) in the future.

7. ACKNOWLEDGEMENTS

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