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AN OPTIMAL-ESTIMATION ALGORITHM FOR WATER VAPOR PROFILING USING AMSU

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1. INTRODUCTION

Retrievals of water vapor profiles are required for applications ranging from numerical weather forecasting to climate modeling and climate change studies. As these fields advance, there is an increasing need for weather and climate water vapor studies over complex, cloudy conditions (e.g. Lietzke et al. (2001)). The Advanced Microwave Sounding Unit (AMSU), first flown on board the NOAA-15 satellite in 1998, provides global water vapor measurements in clear and cloudy skies. This broad capability makes it a key instrument for water vapor retrievals. This paper describes an algorithm for the retrieval of water vapor profiles from AMSU. The algorithm has the ability to simultaneously retrieve water vapor profiles, temperature profiles, and microwave surface emissivities. This ability allows for more accurate water vapor retrievals, as is shown using simulated data.

2. ALGORITHM DESCRIPTION

The retrieval algorithm is a physically based iterative optimal-estimation scheme adapted from the method of Engelen and Stephens (1999). The algorithm can take data from AMSU-B, from AMSU-B and AMSU-A combined, or from SSM/T-2. A variety of parameters can be retrieved including profiles of water vapor mixing ratio, joint water vapor and temperature profiles (including surface temperature), and water vapor and temperature profiles along with microwave surface emissivities.

The retrieval scheme requires an a priori guess of the water vapor and temperature profiles as well surface emissivities at the relevant microwave frequencies. This is used to constrain a non-linear iterative optimal-estimation scheme which uses the method of Rogers (1976) to minimize the cost function Φ to find the optimal solution x, where:

$$\Phi = (x - x_a)^T S_a^{-1} (x - x_a) + \{y - F(x)\}^T S_y^{-1} \{y - F(x)\}$$

where x is the vector of parameters to be retrieved, x_a is the a priori vector, y is the set of observations, F(x) is a forward radiative transfer model used to compute radiances given x, and S_a and S_y are the error covariance matrixes of the a priori data and the observations, respectively. The vector of retrieval parameters may include the profile of water vapor mixing ratio alone, or may include the temperature profile and surface emissivities as well. The a priori error covariance matrix includes the variances of and correlations between the retrieval parameters, thus providing a constraint on the solution from a priori knowledge. The error covariance matrix of the observations includes forward model errors and uncertainty in the observed radiances.

For the forward radiative transfer, monochromatic microwave brightness temperatures were computed using numerical integration of the radiative transfer equation for a plane parallel, absorbing atmosphere together with Liebe’s MPM92 (Liebe and Hufford 1993) model of microwave atmospheric attenuation. The Rayleigh-Jeans distribution was used for the source function.

3. AMSU SIMULATIONS

To test the retrieval scheme, simulations of AMSU observations have been created. 100 mid-latitude ocean profiles from the NOAA-88 profile data set have been input to the radiative transfer model to calculate AMSU-A and AMSU-B brightness temperatures. Independent random noise was added to each of the simulated brightness temperatures in order to simulate random sensor uncertainty. The noise was assumed to be Gaussian with a standard deviation set to the temperature sensitivity (NEDT) of the appropriate AMSU channel. Table 1 presents the characteristics used to simulate the AMSU instruments. The temperature of the lowest level of the NOAA-88 profile was taken as the surface temperature. This surface temperature, together with a randomly chosen surface wind speed taken from the SSM/I sea surface wind speed cal/val distribution, were input to the ocean surface model of Yueh (1997) to

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compute microwave emissivities at the appropriate frequencies.

The first guess for the retrieval algorithm was obtained by adding noise to the original NOAA-88 profile. The noise was assumed to be Gaussian with the parameters presented in Table 2 and is correlated using the correlation matrix calculated from the entire set of NOAA-88 mid-latitude ocean profiles.

The a priori error covariance matrix S_a was computed using the errors of the first guess in Table 2 along with the correlations for the retrieval variables calculated from the entire set of NOAA-88 mid-latitude ocean profiles. The error covariance matrix for the observations, S_y, was computed using the AMSU characteristics in Table 1. The AMSU channels were assumed to be uncorrelated. Forward model error was not included in Sy, since the effects of forward model error should be negligible for simulated data where the simulations use the same forward model as the retrieval scheme.

	Channel	**Frequency (GHz)**	**NEDT (K)**
AMSU-A	1	23.8	0.3
	2	31.4	0.3
	3	50.3	0.4
	4	52.8	0.25
	5	$53.596 \pm .115$	0.25
	6	54.4	0.25
	7	54.94	0.25
	8	55.5	0.25
	9	$57.290344 = f_0$	0.25
	10	$f_0 \pm .217$	0.4
	11	$f_0 \pm .3222 \pm .048$	0.4
	12	$f_0 \pm .3222 \pm .022$	0.6
	13	$f_0 \pm .3222 \pm .010$	0.8
	14	$f_0 \pm .3222 \pm .0045$	1.2
	15	89.0	0.5
AMSU-B	1	89.0	0.8
	2	150.0	0.8
	3	183.31 ± 1.0	0.8
	4	183.31 ± 3.0	0.8
	5	183.31 ± 7.0	0.8

Table 1. AMSU characteristics used in simulations.

Parameter	**Std. Deviation**	**Source**
Water Vapor Mixing Ratio	0.0005-2.1 g/kg (see figure 2)	English (1999)
Temperature	3.0 K	Nutter et al. (1999)
Emissivity	.01	2 m/s wind speed and 3.0 K surface temperature uncertainty

Table 2. Magnitude of first guess errors.

4. RESULTS

The algorithm has been used to retrieve profiles from the simulated data for a number of different cases. One set of cases uses AMSU-B data, while the other uses both AMSU-A and AMSU-B for the same set of 100 profiles. Retrievals of water vapor profiles only, joint retrievals of temperature and water vapor profiles, and joint temperature, water vapor and emissivity retrievals have been run. For AMSU-A, three emissivities are retrieved with the 50-60 GHz channels grouped into one emissivity. For AMSU-B, three emissivities are retrieved with all of the channels centered around 183 GHz grouped into one emissivity. For each of the 100 profiles, the appropriate brightness temperatures have been simulated and input to the retrieval scheme for each retrieval case described above. An example of a retrieved mixing ratio profile for both AMSU-B and AMSU-A data retrieving water vapor, temperature, and surface emissivities simultaneously is shown in Figure 1. The retrieved profiles are then compared to the original and an rms error as well as a mean bias has been computed for each level of the profile. Table 3 contains the profile averaged rms error, bias, and maximum bias for the data set broken down by retrieval case.

Figures 2 through 4 show the water vapor mixing ratio profile errors for the AMSU-B retrievals for water vapor profile retrieval only, temperature and water vapor profile retrieval, and temperature and water vapor profile along with surface temperature and surface emissivity retrieval respectively. With just AMSU-B data, the retrieval should be sensitive primarily to the water vapor. However, a reduction in retrieval error, particularly in retrieval bias, is seen in going from water vapor only to water vapor, temperature, and emissivity retrievals. While there is some temperature and emissivity information in the AMSU-B channels, this improvement of the water vapor retrievals by simultaneously retrieving temperature and surface emissivity along with water vapor is in large part due to the constraint provided by the a priori error covariance matrix S_a. If only the water vapor profile is retrieved, then the water vapor profile must compensate for first guess errors in temperature profile and surface properties. This compensation shows up primarily as bias in the retrieval that disappears as the retrieval of a temperature profile and surface emissivities are added. The a priori error covariance matrix helps to constrain the temperature and emissivity retrievals by correlating them to the retrieved water vapor profile. Some residual bias from the retrieval scheme remains even when water vapor, temperature, and emissivity are retrieved.

Figures 5 through 7 show the three different retrieval cases with both AMSU-B and AMSU-A data. The water vapor retrieval errors for all three cases are reduced in going from the water vapor retrieval only to the water vapor, temperature, and emissivity simultaneous retrieval. With both AMSU-B and AMSU-A data, both water vapor and temperature profiles can be directly retrieved, thus further improving the water vapor profile retrieval. As shown in Table 3, the AMSU-B and AMSU-A water vapor retrievals do better (i.e. have lower mean rms error and lower bias compared to truth) than the AMBU-B retrievals when temperature is simultaneously retrieved. The water vapor only retrieval, though, is better using just the AMSU-B data. The AMSU-A data don't contain much direct information about water vapor. Without the temperature retrieval, the effect of the AMSU-A data is to add noise to the retrieval.

Data	Retrieval Type	Mean RMS Error (g/kg)	Mean Abs. Bias (g/kg)	Max. Abs. Bias (g/kg)
AMSU-B	Water Vapor Only	.33	.08	.20
	Water Vapor + Temperature	.28	.06	.19
	Vapor + Temp + Emissivity	.23	.03	.08
AMSU-B and AMSU-A	Water Vapor Only	.37	.10	.32
	Vapor + Temperature	.25	.03	.11
	Vapor + Temp + Emissivity	.18	.02	.06

Table 3. Statistics for the water vapor mixing ratio retrievals averaged over the profile levels. Mean and maximum biases are for the absolute value of the bias.

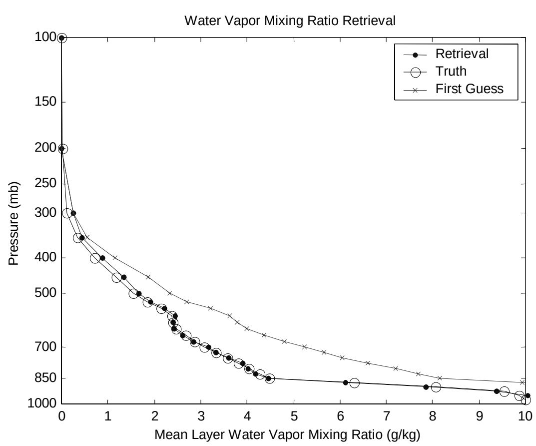

Figure 1. Retrieved, true, and first guess water vapor mixing ratio profiles from AMSU-B and AMSU-A data for a simultaneous water vapor, temperature and surface emissivity retrieval.

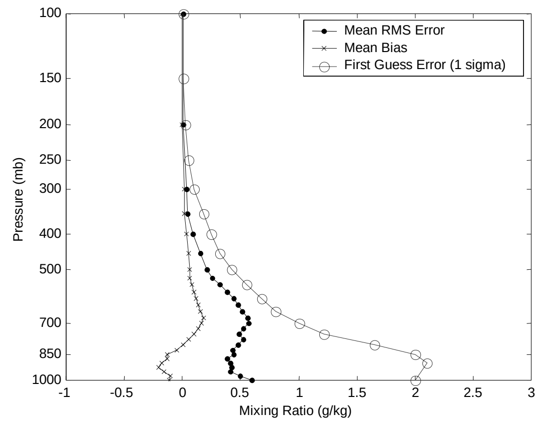

Figure 2. Errors from AMSU-B retrieval of water vapor mixing ratio. Only water vapor was retrieved.

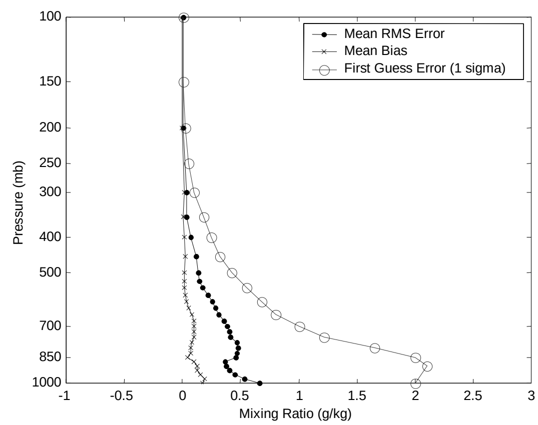

Figure 3. Errors from AMSU-B retrieval of water vapor mixing ratio. Water vapor and temperature profiles were retrieved simultaneously.

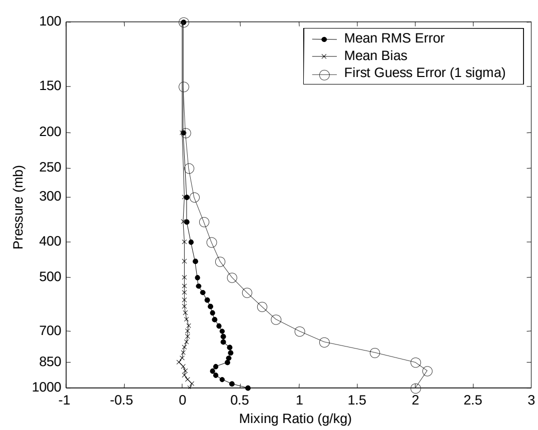

Figure 4. Errors from AMSU-B retrieval of water vapor mixing ratio. Water vapor and temperature profiles as well as surface emissivities were retrieved simultaneously.

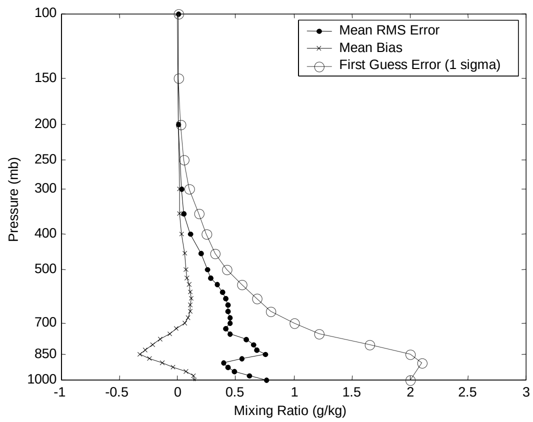

Figure 5. Errors from AMSU-B and AMSU-A retrieval of water vapor mixing ratio. Only water vapor was retrieved.

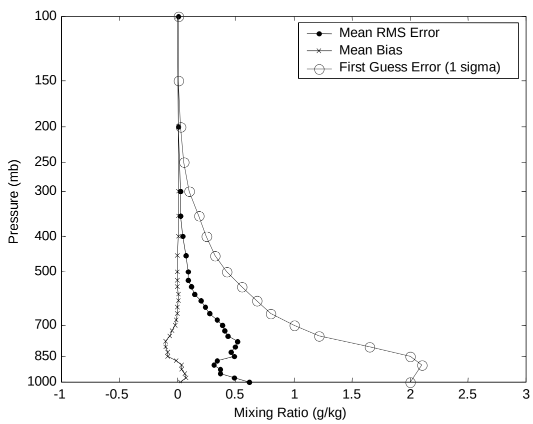

Figure 6. Errors from AMSU-B and AMSU-A retrieval of water vapor mixing ratio. Water vapor and temperature profiles were retrieved simultaneously.

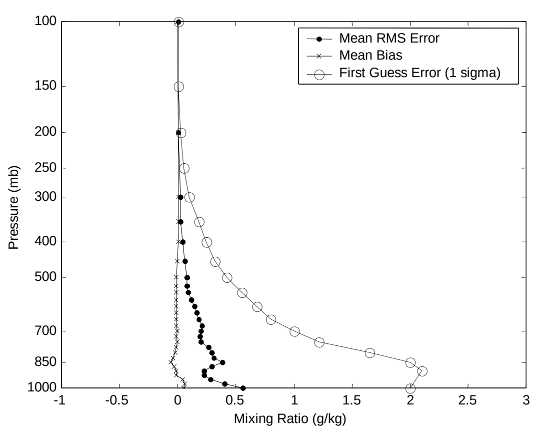

Figure 7. Errors from AMSU-B and AMSU-A retrieval of water vapor mixing ratio. Water vapor and temperature profiles as well as surface emissivities were retrieved simultaneously.

5. CONCLUSIONS AND FUTURE WORK

An algorithm for the retrieval of water vapor profiles from AMSU has been presented. The algorithm is quite general, in that it can be applied to data from AMSU as well as other satellite platforms such as SSM/T-2 and the upcoming SSM/IS instrument, which should become available in 2002. Water vapor profiles can be retrieved with or without profiles of temperature profiles and surface emissivities. It was shown using simulated AMSU-A and AMSU-B measurements that, even with AMU-B measurements alone, water vapor retrieval performance is improved for the case of simultaneous water vapor, temperature, and emissivity retrievals. Future work will concentrate on applying the algorithm over land and to cloudy conditions.

6. ACKNOWLEDGMENTS

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