1DVAR RETRIEVALS OF HUMIDITY: HOW USEFUL ARE SSM/T-2 BRIGHTNESS TEMPERATURES?

Godelieve Deblonde
Atmospheric Environment Service
Dorval, Quebec, Canada

Summary: 1DVAR retrievals of humidity using DMSP SSM/T-2 synthetic brightness temperatures are evaluated for clear and cloudy (non-raining) profiles over the open oceans.

1. INTRODUCTION

The retrieval of the vertical distribution of humidity with a 1DVAR (one-dimensional variational) assimilation system is studied using synthetic brightness temperatures (STB's) for the DMSP SSM/T-2 (special sensor microwave water vapor sounder). Analyses are performed in clear and cloudy skies over the open oceans.

The first operational SSM/T-2 instrument was on board the F11 satellite launched in 1991. The instrument characteristics for the SSM/T-2 and the NOAA-K AMSU-B (launched in 1998) are similar (Table 1). The main differences are the size of the field of view and the mixed polarization. For the SSM/T-2, the mixed polarization becomes horizontal as the instrument view angle tends to nadir and vertical for the AMSU-B. The polarization specification for the SSM/T-2 is at a disadvantage since horizontally polarized TB's are more sensitive to surface parameters which are more difficult to model.

TABLE 1:
DMSP SSM/T-2 channel parameter specifications
(28 scan positions between ±40.5° from sub-satellite point)

Central Frequency (GHz)	First Sideband (GHz)	Half Bandwidth (MHz)	Polarization Angle at Nadir	Ground Resolution (km)	NEΔT
91.655	1.25	750	H	84	0.6
150.00	1.25	750	H	54	0.6
183.31	1.0	250	H	48	0.8
183.31	3.0	500	H	48	0.6
183.31	7.0	750	H	48	0.6
NOAA-K AMSU-B channel parameter specifications (90 scan positions between ±48.95° from sub-satellite point)					
89.00	0.9	500	V	16.3	0.37
150.00	0.9	500	V	16.3	0.84
183.31	1.0	250	V	16.3	1.06
183.31	3.0	500	V	16.3	0.7
183.31	7.0	1000	V	16.3	0.6

2. 1DVAR ASSIMILATION SYSTEM

The 1DVAR system was developed over several years at ECMWF (e.g. Phalippou 1996). The optical depths of the 1DVAR fast radiative transfer model (RTM) are obtained using regression equations (Eyre

1991) that contain a large number of predictors. New predictors for the 183 GHz water vapor absorption channels were implemented (Deblonde 1999a) that greatly reduce the discrepancy between the fast RTM and a microwave line by line RTM model implemented at AES.

The 1DVAR in its original form was developed to process SSM/I (special sensor microwave/imager) TB's. The ocean surface emissivity is modeled with a geometric-optics model which simulates the large-scale roughness. A model of sea-foam is included. To simulate cloud water absorption, the Rayleigh approximation is used. The 1DVAR was adapted to process SSM/I and/or SSM/T-2 TB's. As a result, the modified 1DVAR can use 2 sets of optical depth predictors, can handle mixed polarization and a variable earth incidence angle with scan position. The control variable x consists of the natural logarithm of specific humidity (ln q) for 15 fixed pressure levels between 1000 and 300 hPa, the surface wind speed (SWS) and the cloud liquid water path (CLW). For cloudy profiles, CLW is retrieved while the cloud structure function is maintained fixed to that of the background field. If no clouds are present in the background field, then a first guess cloud is produced. For most profiles, only the lowest frequency of the SSM/T-2 is somewhat dependent on SWS. As a result, the variation of SWS was set to zero. The cost function *J(x)* may be written as:

$$J(x) = (x - x^b)^T B^{-1}(x - x^b) + (y^o - H(x))^T (O + RT)^{-1} (y^o - H(x)) + J_{SAT}$$

where B, O and RT are respectively the background, the observation and forward model (fast RTM) error covariance matrices. J_{SAT} is a function that controls the supersaturation (Phalippou 1996). The satellite observations are denoted by y^O and x^b are the collocated background profiles obtained from GEM (Global Environmental Multiscale model, Côte et al. 1998) 6-h forecasts. GEM has been operational at the Canadian Meteorological Center since October 1998 and includes a prognostic equation for cloud water. *H* is the fast RTM model. The background error covariances for ln q are those used in the operational 3DVAR assimilation system (Deblonde 1999b). The background error for CLW was set to 0.2 kgm^{-2}.

O+RT was obtained by first computing the standard deviation between the observed TB's and those modeled with the 1DVAR forward model (referred to as O-F). O-F values are listed in Table 2. O+RT is taken to be a fraction of O-F and is set equal to $\sqrt{(2/3)}$ as in Chouinard and Hallé (1999). O-F was computed for the first 15 days of September 1998 (DMSP F14 SSM/T-2). The 1DVAR assimilation results discussed below were performed with STB's obtained with background profiles for 15 September 1998 00Z $\pm$ 3 h.

In the 1DVAR system, observed SSM/T-2 TB's were simply replaced with STB's computed using the fast RTM with the background or "true" profiles. It was also assumed that the bias between the modeled TB's and STB's (which now replace the observed values) is zero. Observations were limited between 20^{o}S and 20^{o}N. The minimum TPW (total precipitable water) value was 15.0 kgm^{-2}.

TABLE2: SSM/T-2 O-F for Sep 1-15, 1998 (00,06,12,18Z)

Clear-sky cases only. Clouds were filtered using CLW obtained from the regression equation of Weng and Grody (1994) using SSM/I TB's. SSM/T-2 TB's were collocated with SSM/I TB's.

Frequency	O-F	O+RT
(GHZ)	(K)	(K)
92	4.65	3.8
150	3.83	3.1
183 (1)	4.53	3.7
183 (3)	3.75	3.1
183 (7)	3.19	2.6

Retrievals with STB's were also performed for which O+RT=0.01B_E where B_E is the effective background error in TB space. $B_E = H'(X)BH'^T(X)$ where $H'(X)$ is the jacobian of the fast RTM. For such cases, the satellite data assimilation is "strong" since the observation error is set to be much smaller than the background error.

3. CLEAR-SKY RETRIEVALS USING SYNTHETIC BRIGHTNESS TEMPERATURES

1DVAR retrieval results are presented for 4 cases named A to D which are defined in Table 3. For case A, the background q profile (q^b) was set to 0.9 q_{true} where q_{true} is the true specific humidity profile. The background SWS was set to its true value SWS_{true}. O+RT=0.01 B_E for each profile and thus the assimilation must be strong. The TPW retrievals for case A are nearly perfect. The statistic to evaluate this is defined as $Y=100.*(TPW_{analyzed}-TPW_{true})/TPW_{true}$ and thus Y is in %. The mean of Y is 0.05% and its standard deviation (SD) is 0.12%. These Y statistics will further be denoted as a pair, e.g (mean, SD). Fig. 1a illustrates the mean difference between the 1DVAR solution q and the background value normalized by q_{true}. The mean is taken over all profiles common to cases A to D for which the 1DVAR converged. Perfect retrievals would give a mean difference of 10%. Fig. 1b illustrates the root mean square (RMS) in % of the solution q and its true value normalized by its true value. A RMS of 10% implies that the solution equals the background value. Although TPW retrievals are quite accurate, the retrieval accuracy of q varies with height. This accuracy depends on the background error vertical correlations (which smooth out the profiles and effectively increase the background error), the vertical distribution of the error variance and the shape of the weighting functions. The maximum q RMS is ~2% at 700 hPa.

TABLE 3: CLEAR PROFILES EXPERIMENT SET UP

Case	q^b	SWS^b	O+RT	Temperature
A	0.9 q_{true}	SWS_{true}	0.01B_E	T_{true}
B	0.9 q_{true}	SWS_{true}	Table 2	T_{true}
C	0.9 q_{true}	0.7 SWS_{true}	Table 2	T_{true}
D	0.9 q_{true}	SWS_{true}	Table 2	T_{true}+1K

The Y statistics for case B which has "realistic" observation errors are (-1.25%,0.15%) and show that TPW is underestimated. The magnitude of O+RT is such that it does not lead to a full recovery of the "true" TPW. The maximum RMS is around 4% at 700 hPa. Setting the background profile equal to a fraction of 0.8, 1.2 and 1.5 of the true profile instead of 0.9 gave similar statistics. Reducing the O+RT values would of course lead to fuller recoveries.

The impact of reducing the SWS by 30% (Case C) was to increase the mean of the TPW retrievals (-0.213%,0.6%) and the SD. The impact on the vertical distribution of humidity was to increase the mean q by as much as 1.2% in the lower troposphere (Compare Cases B and C in Fig. 1a). A perturbation value of 30% was chosen because a SWS error of 2 ms^{-1} for a globally averaged oceanic wind speed of ~7 ms^{-1} would give about that value. Increasing the temperature profiles by 1K at all levels (Case D) resulted in a large overestimation of the q retrievals in the upper troposphere, this is not surprising since the 183 GHz channels are sensitive to temperature as well as to humidity. The lower troposphere humidity retrievals are also affected (underestimated) but not by as much. This was also to be expected since the 92 GHz channel is a window channel that is not as sensitive to temperature. The 150 GHz channel behaves as a window or sounding channel depending on the amount of TPW.

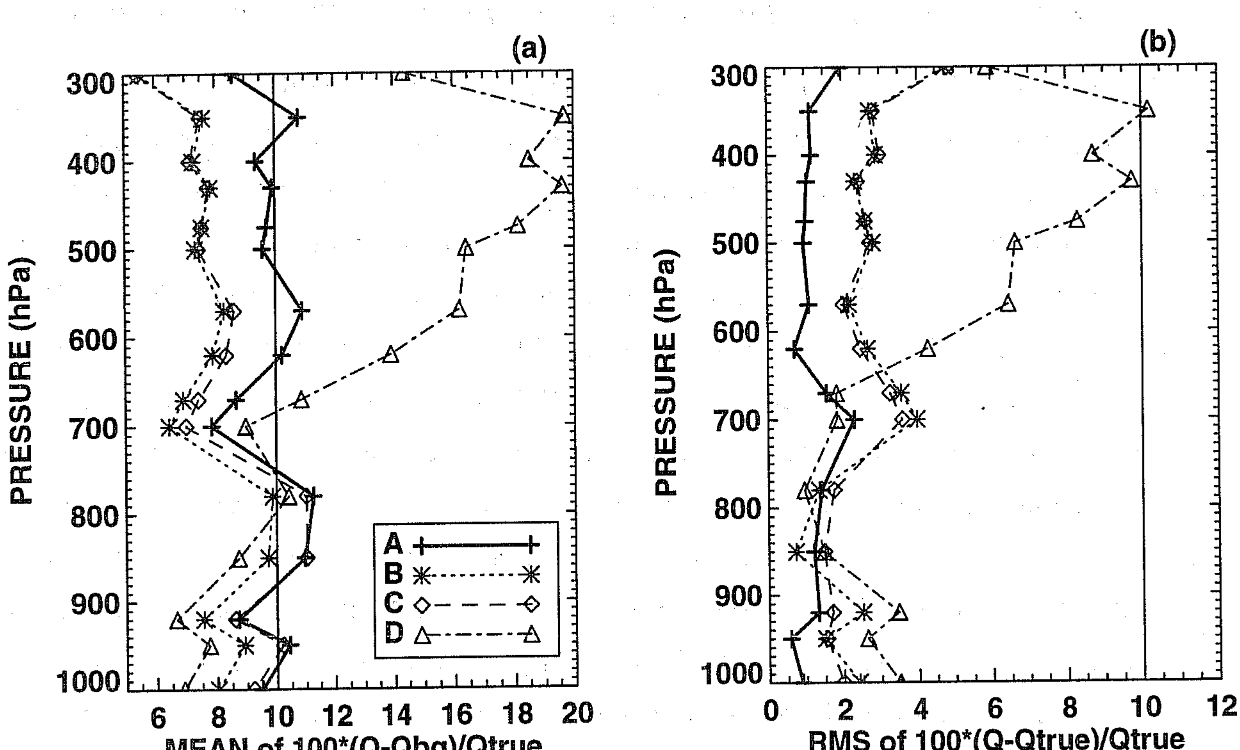

Fig. 1: Clear sky specific humidity retrieval statistics for cases A, B, C and D (defined in Table 3) for 15 September 1998 00Z, N=2400. a) Percent mean difference between the analyzed q and the background value normalized by the true value. b) Percent root mean square (RMS) of the analyzed q and its true value normalized by its true value.

4. IMPACT OF THE PRESENCE OF CLOUDS (NON-RAINING) ON HUMIDITY RETRIEVALS

Retrievals of humidity in the presence of 6-h GEM forecast clouds were performed. The model CLW values are low with most grid points reporting CLW < 0.1 kgm^{-2} . The maximum CLW is 0.32 kgm^{-2}. The resolution of the GEM model is 100 km at the equator. The CLW values depend on the choice of partition function (depends only on temperature) that splits the cloud water into its liquid and solid components (Deblonde et al. 1997). A linear function was used here. The q retrieval statistics were computed for different classes of CLW defined in the figure caption of Fig. 2. Even for very low amounts of CLW, the presence of clouds has a large impact on the retrieval of q in the lower troposphere. A 4% decrease in recovery (change in RMS) occurs at 950 hPa for CLW values between 0.2 and 0.32 kgm^{-2} (Case D).

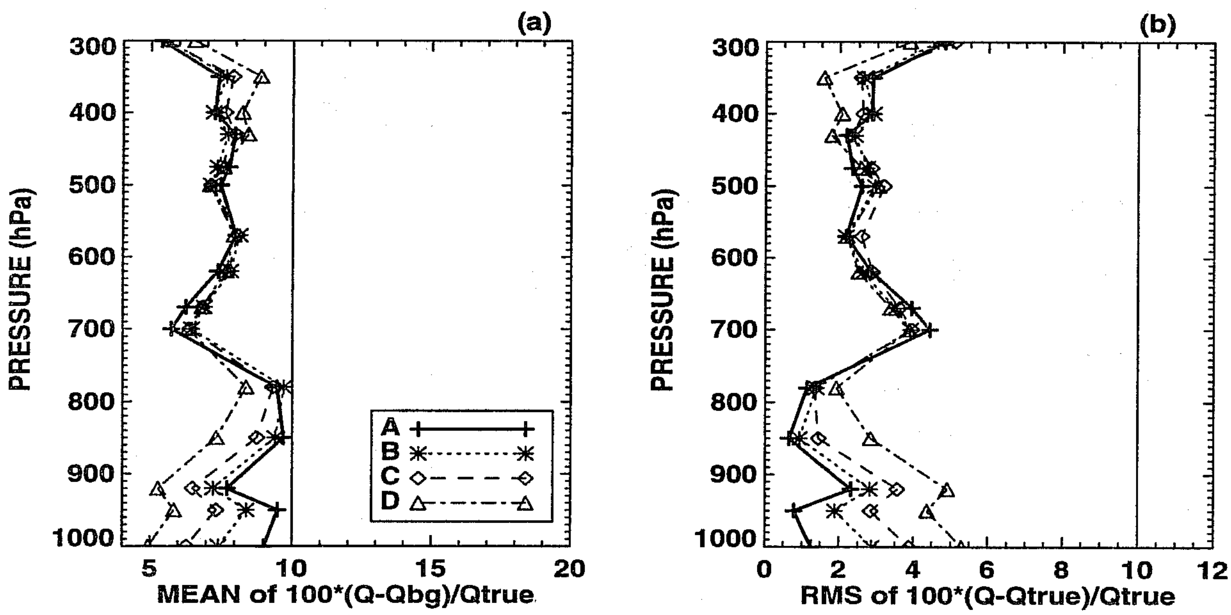

Fig. 2: Cloudy sky specific humidity retrieval statistics for cases A (CLW <0.01 kgm^{-2}), B (CLW >0.01 and < 0.1 kgm^{-2}), C (CLW >0.1 and < 0.2 kgm^{-2}) and D (CLW >0.2 kgm^{-2}) for 15 September 1998 00Z. Retrieval statistics have the same definition as in Fig. 1, N=2457.

In case the model background would produce more CLW, further experiments were performed with a uniform distribution of "synthetic" clouds. The properties of the clouds that were fabricated are given in Table 4. It is generally stated that profiles with CLW > ~0.5 kgm^{-2} should contain rain water as well as cloud water and thus the synthetic CLW values were chosen to be less than 0.7 kgm^{-2}. Fig. 3 illustrates the rapid deterioration of q retrievals as the CLW increases with about a 1% deterioration for each increase in CLW of 0.1 kgm^{-2}. Therefore, even over the oceans, retrievals of profiles of specific humidity below cloud tops are expected to be feasible only in the presence of thin clouds (< 0.1 kgm^{-2}). The

1DVAR is set up to also retrieve CLW. CLW retrievals from the SSM/T-2 TB's were attempted but it was quickly concluded that retrievals were not possible.

TABLE 4: SYNTHETIC CLOUDS

CASE	CLW (kgm^{-2})	CLOUD BASE PRESSURE (hPa)	CLOUD TOP PRESSURE (hPa)
A	NO CLOUDS:	same as section 3 case A.	
B	0.1	950	800
C	0.1	750	700
D	0.2	950	800
E	0.2	750	700
F	0.2	950	900
G	0.3	950	900
H	0.4	950	750
I	0.5	950	750
J	0.7	900	650

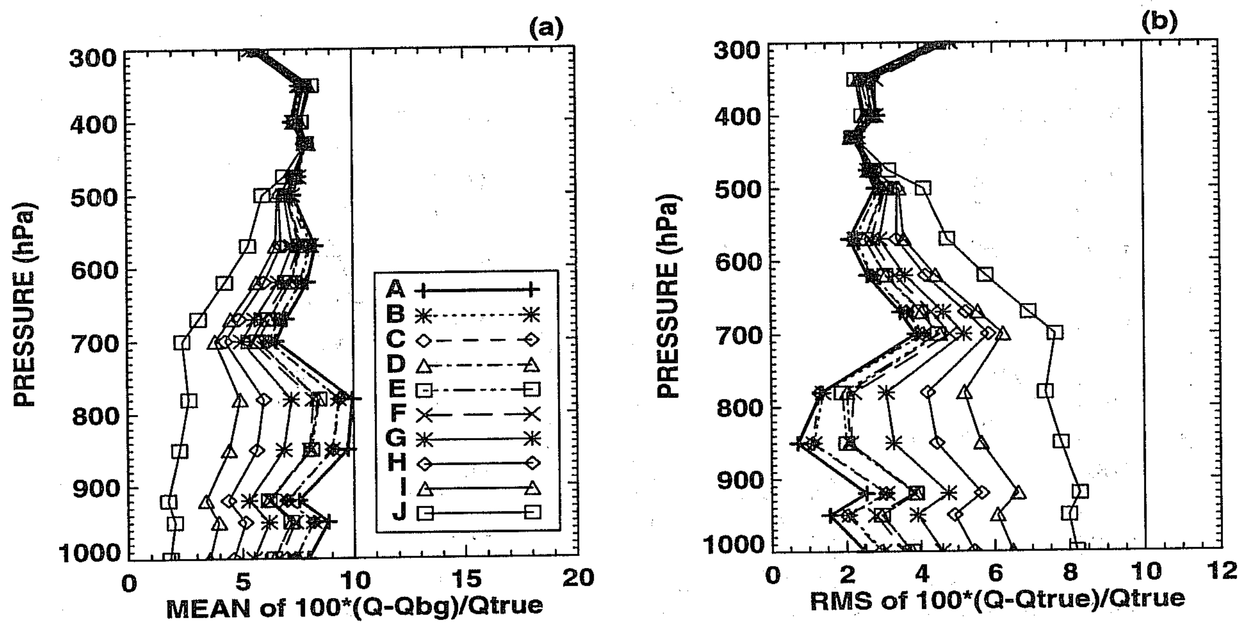

Fig.3: Cloudy sky specific humidity retrieval statistics for cases as listed in Table 4 and for 15 September 1998 00Z. Clouds were produced synthetically. Retrieval statistics have the same definition as in Fig. 1, N=2457.

5. CONCLUSION

1DVAR retrievals of humidity using DMSP SSM/T-2 synthetic brightness temperatures were evaluated for clear and cloudy (non-raining) profiles over the open oceans. Clear sky retrievals of TPW are nearly perfect when a very small observation error (compared to the background error) is used. This result is so good in part because error cancellation occurs in the vertical as the q retrieval accuracy varies with height. When realistic values of O+RT are used, the TPW is somewhat underestimated and so are the humidity profiles. The assimilation of the STB's therefore is strong but not complete. Errors in SWS (especially for drier atmospheres) and air temperature affect the accuracy of the q retrievals mostly in the lower troposphere for SWS and upper troposphere for temperature.

As was shown previously with a statistical regression type of retrieval (Isaacs and Deblonde 1987), the presence of clouds can largely affect the retrievals of profiles of specific humidity. Specific humidity retrievals should be attempted only in the presence of thin clouds. It is clear also that CLW retrievals with SSM/T-2 TB's should not be attempted either as these were shown to be unsuccessful in the 1DVAR retrieval context. If O+RT were reduced for all channels, then the q retrievals would get closer to the true solution. Decreasing O+RT would require a more accurate forward model of the surface and coincident retrievals of temperature since the 183 GHz water vapor channels are also sensitive to temperature. Retrievals of humidity alone in the upper troposphere should probably not be attempted if there are known problems with the temperature profiles.

6. REFERECENCES

Côte, J., S. Gravel, A. Méthot, A. Patoine, M. Roch, A. Staniforth, 1998: The operational CMC-MRB Global Environmental Multiscale (GEM) model. Part I: Design considerations and formulation, *Monthly Weather Review*, **126**, 1373-1395.

Chouinard, C and J. Hallé, 1999: The impact of TOVS radiances in the CMC 3D variational assimilation system. Proceedings of the tenth international TOVS study conference, Boulder, CO, 27 January -2 February 1999.

Deblonde, G., W. Yu and L. Garand, 1997: Evaluation of global NWP analyses and forecasts using DMSP SSM/I retrievals. 2. Analyses/forecasts intercomparison with SSM/I retrievals, *J. Geophys. Res.*, **102**, 1851-1866.

Deblonde, G., 1999a: Variational assimilation of humidity using SSM/T-2 brightness temperatures. Proceedings of the tenth international TOVS study conference, Boulder, CO, 27 January -2 February 1999.

Deblonde, G., 1999b: Variational assimilation of SSM/I total precipitable water retrievals in the CMC Analysis system, *Monthly Weather Review*, **127**, 1458-1476.

Isaacs, R.G. and G. Deblonde, 1987: Millimiter wave moisture sounding: The effect of clouds. *Radio Science*, **22**, 367-377.

Eyre, J.R., 1991: A fast radiative transfer model for satellite sounding systems. ECMWF Tech. Memo 176.

Phalippou, L., 1996: Variational retrieval of humidity profile, wind speed and cloud liquid water path with the SSM/I: Potential for numerical weather prediction., *Q. J. R. Meteorol. Soc.*, **122**, 327-355.

Weng, F. and N.C. Grody, 1994: Retrieval of cloud liquid water using the special sensor microwave imager (SSM/I), *J. Geophys. Res.*, **99**, 25 535- 25 551.