THE IMPACT OF TOVS RADIANCES IN THE CMC 3D VARIATIONAL ANALYSIS SYSTEM

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1. INTRODUCTION

In June 1997, the CMC implemented its first global 3D-var analysis system for the preparation of daily 10-day forecasts (Gauthier et al. 1998). In the fall of the same year, this incremental 3D-var was introduced for the preparation of the 35-km regional model analyses (Laroche et al. 1998). Both the global and regional systems produce increments on a 16 pressure level grid with the top analysis and forecast level at 10 hPa. In their first implementation, because geopotential is used as mass variable and not temperature, it was decided to retain SATEM thickness’ as the main source of satellite data for analysis. In this study, the operational suite is compared to an experimental suite that uses TOVS radiances at equivalent horizontal resolution.

In preparation for the use of higher resolution ATOVS radiance data of NOAA-15, research in radiative transfer modeling (RTM) for the purpose of characterizing errors has progressed significantly (Garand et al. 1999, Saunders et al. 1998). However, because of radiance data pre-processing and errors in the fast RTM, unacceptably large biases remain in some channels remain and these must be corrected prior to assimilation in order to get positive impact from the TOVS radiances. Monitoring has been integrated into the 3D-var system and is critical to control the quality of TOVS radiances. From the QC-controlled dataset, biases are first estimated and then removed after which observational errors are obtained. The biases and random errors are further monitored from within the 3D-var itself to insure that the biases of each TOVS channel remain very small and that the a priori specified observational errors remain valid throughout a 30-day cycle. In particular, the residual scan biases that are present in each channel are systematically monitored throughout the assimilation period and over large latitudinal bands to insure they remain small in all regions at all time.

Comparisons with the operational 3D-var/SATEM system are presented with emphasis on the response to radiance data. Results clearly indicate that the assimilation of radiances consistently produces better analyses as indicated by improved 6-h, 2, and 5-day forecasts.
As proposed by Parrish and Derber (1992) and Courtier et al. (1994), and without any loss of
generality, the 3D-var formulation of this study is based on the incremental approach. For
the incremental approach, the functional that is minimized is expressed as,

\[ J(\Delta \tilde{X}) = (\Delta \tilde{X})^T B^{-1}(\Delta \tilde{X}) + (H'(\Delta \tilde{X}) - R')^T O^{-1}(H'(\Delta \tilde{X}) - R') \]  

(1)

where \( R' = R - H(X_b) \) are the observed innovations, and \( \Delta \tilde{X} \) are the analysis increments.
The innovations \( R' \) are computed in observation space using the full resolution background
state \( X_b \), whereas the analysis increments \( \Delta \tilde{X} \) are calculated at lower resolution. In this
study, the trial fields are used at full T199 spectral resolution and the analysis increments
\( \Delta \tilde{X} \) are calculated at the lower T108 spectral resolution. This formulation is general enough
to allow the use of higher vertical resolution trial fields to calculate the observed innovations.
This was not exploited in this version.

2.1 Use of TOVS data: monitoring and quality control (QC)

The radiance data used for this study is the so-called revised TOVS (RTOVS) of
NOAA/NESDIS for the NOAA-11 and 14 platforms (Paris 1997). It has undergone a number
of adjustments which are judged useful/necessary before the data is assimilated. Without
going into details, the main adjustments are:

i) limb adjustment; the data is adjusted to remove the so-called limb cooling effect due to
longer atmospheric paths away from nadir view. In some channels the corrections due to
this effect are of several degrees and understandably the statistical regression method used
at NESDIS for this correction is not perfect and leaves residual scan biases of the order of
a degree in some channels. Unfortunately this is unacceptably large because it is of the
same order as the random errors. In Fig. 1a, the residual scan biases of NOAA-14 for the
month of June 1998 are presented as a function of scan position. Some channels display
small errors either because the limb adjustment was very successful or because there was
no significant adjustment to do. Others such as HIRS 1, 7, and 8 have errors exceeding 1
degree. Note that the errors in the microwave channels are relatively small.
ii) the RTOVS data is cloud-detected and classified as clear or cloudy. The cloud-detection method works well but occasionally cloudy pixels will erroneously be reported as clear. Fortunately, simulated window channels 8 and 10 based on the 6-h background can be used to check these data and reject them if needed.

In preparation for data assimilation, all RTOVS data are subject to the following quality control (QC). First, a gross quality check to ensure BT’s fall within the (150, 350) degree range. Secondly, in an attempt to isolate problems that NESDIS may have encountered at the cloud-detection step, simulated RT model brightness temperatures in channel 10 are compared to observations in the same channel, if they differ by more than -15, -8, and -4 over land, ice and water respectively, the data are rejected. Finally, a Rogue test is applied, that is, if the difference to observations in any channel is larger than 4 standard deviations of the a priori estimate, the whole profile is rejected. Generally less than 7% of the data are rejected by the QC. The largest reduction in data is obtained by dropping the cloudy data which is very difficult to assimilate, and eliminating data at the extreme left and right of the swath (positions 1,2,17, and 18 in Fig. 1a)

Finally, the data is thinned down to an equivalent 250 km resolution for assimilation. In practice this translates in a reduction to 2000 TOVS radiance profiles per 6h compared to 2500 SATEM profiles per 6h as currently used in the operational system.

2.2 Bias correction of the RTOVS data

It was shown in the previous section that significant residual scan biases are present in the data. There are also significant errors at nadir that cannot be related to limb adjustments and the data itself. These are related to deficiencies in the RTM model and are referred to as air-mass dependent biases. There have been various approaches proposed to remove these. Eyre (1993) proposed a two-pass system; in the first pass the global scan biases are estimated and removed and in the second pass the air-mass biases are removed by projecting the error onto a set of air-mass predictors. As in Derber and Wu (1998), the system we are currently using is a one-pass system that projects the biases onto an extended set of predictors made up of 6 observed brightness temperatures (BT) and two scan positional parameters. The system consists of a set of equations (one per channel j) to correct the air-mass bias. It can be described by the following:
\[
\langle \Delta T_i \rangle = \sum_{p=1}^{8} a_{i,j} P_i + b_j \quad \text{where} \quad P_i = S1, S2, S3, M2, M3, M4, p, p^2
\]  
(2)

where \( \langle \Delta T_i \rangle \) are the corrections and the predictors \( p = S1, S2, S3, M2, M3, M4, p, p^2 \) are respectively, three SSU and three microwave observations, and \( p \) is a positional parameter (-9, -8, ..., 0, ..., 8, 9). The SSU predictors are not used in assimilation but used in the bias correction procedure to correct gross errors introduced by extrapolating the background temperature from 10 to 0.1 hPa. The coefficients \( a_{i,j} \) and \( b_j \) are obtained by regression. Note that the positional parameters are able to remove both a linear trend and a quadratic dependence in the scan bias errors.

This bias-correction procedure does exceptionally well in removing both the global and regional biases. In Fig.1b the scan biases of latitudinal band 30-60 S have been corrected and it is evident when compared to Fig. 1a that most of the biases in each channel are practically eliminated. The two-pass system that we used previously (Chouinard and Hallé, 1997) eliminated global biases efficiently but generally left significant regional airmass and scan biases.

2.3 Monitoring the biases and the random errors using the penalty function within the 3D-var

Even though much care is taken to remove the biases from the data, it is important to verify that the ensemble mean of the innovations \( H'(\Delta \bar{X}) - R' \) as measured within the 3D-var is truly zero. Fortunately, when constructing \( \bar{J}_o(\Delta \bar{X}) \), the innovations are stored in a master file by channels for each of NOAA-11 and 14 and normalized by the observational error. It is convenient to construct the ensemble means of the innovations and mean square errors defined as:

\[
\bar{M}_o(\Delta \bar{X}) = 1/N (H'(\Delta \bar{X}) - R')/\sigma_o
\]  
(3)

and

\[
\bar{J}_o(\Delta \bar{X}) = 1/N ((H'(\Delta \bar{X}) - R')/\sigma_o)^2
\]  
(4)

where \( N \) is the total number of data in that channel in a 6-h period. Since \( \sigma_o \) is estimated from the QC monitoring step, both measures of \( \bar{M}_o(\Delta \bar{X}) \) and \( \bar{J}_o(\Delta \bar{X}) \) measure biases and mean square error in units of \( \sigma_o \). Interestingly, the observational error specified in our system is based on partitioning variance equally amongst the three sources of error. The total error

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from the monitoring step is the sum of background \( (\sigma_b^2) \), forward model \( (\sigma_F^2) \) and instrument noise \( (\sigma_o^2) \). The effective observational error specified is the sum of \( (\sigma_o^2 + \sigma_F^2) \) and is, in our system, a fixed fraction \( \alpha^2 = 2/3 \) of the total error \( (\sigma_o^2 + \sigma_F^2 + \sigma_b^2) \). This means that the normalized mean square error \( J_o(\Delta X) \) should from large samples N be \( 1/\alpha^2 = 3/2 \). As can be seen from Fig. 2, the perceived trace of the bias \( M_o(\Delta X) \) during the 30-day assimilation is indeed zero, and the mean square error \( J_o(\Delta X) \) oscillates around a constant 3/2. In some channels, \( J_o(\Delta X) \) is actually decreasing. This is a confirmation that the mean square error \( J_o(\Delta X) \) as measured in radiance space is decreasing with every cycle of the assimilation, generally a good indicator that the system is improving with the use of the radiance data.

3. RESULTS FROM ASSIMILATION CYCLES; COMPARISON TO SATEM AND EVALUATION

The 3Dvar using RTOVS radiance observations was tested during a period in June 1998 and compared to a CONTROL using SATEM. Both systems used all other conventional observations as well. Every 12h during the assimilation, 5-day forecasts were prepared from each of the SATEM and TOVS cycles.

A good measure of performance is the comparison of the two systems 5-day forecasts against a common radiosonde observation set. In Fig. 3, the 6-h, 2-day, and 5-day error statistics against radiosondes are shown for the TOVS (thin lines) and SATEM (full lines) system. Over the NH (Fig. 3a), geopotential, and particularly wind errors, are significantly smaller when using radiances. In the southern hemisphere (Fig. 3b), the improvements are somewhat smaller, indicating that the current SATEM system is doing reasonably well there. Note that on the average, the improvements in the 6-h background prevail throughout the 5-day. Finally, in Fig. 4, the rms improvements of each of the sixty (twice per day) 5-day forecasts are presented at 100, 250, 500 and 850 hPa. Clearly, the improvements are very systematic and positive on a case-by-case basis and very few forecasts are worst in the TOVS system.

4. CONCLUSIONS AND FUTURE WORK

A complete 3D-var system has been formulated including a quality control of TOVS radiance observations. External monitoring has been developed to characterize and eliminate sources
of errors before assimilation and to estimate observational errors of RTOVS radiances. Monitoring has been built within the 3D-var to confirm that the a priori specified observational errors are proper and that the biases of the radiance data have been eliminated. This has been a key aspect to arrive at the positive results of this study using radiances.

Preliminary assimilation tests with the TOVS radiances including QC were compared to a system using SATEM retrievals. Over the NH the results of the TOVS system are very positive, particularly over Asia. The results in the SH are also positive and persist in the forecast for at least a period of 5 days.

The variational system is currently being updated and the next version will be formulated in the same hybrid coordinate system as the forecast model and not on 16 pressure levels as in this system. In this revised version, the NWP model moisture above 300 hPa will be used and not extrapolated as currently done. This should be very positive for the assimilation of the TOVS moisture channels.

The ATOVS level-1c data of NOAA-15 are currently being monitored and as soon as the bias correction procedure has been adapted to the HIRS and AMSU-A data, assimilation tests will begin.

5. REFERENCES


Chouinard C. And J. Hallé: The variational assimilation of TOVS radiance observations: formulation and evaluation in 1D and 3D mode. ITSC-IX proceedings, Igls Austria, February 1997, p.65-75.


