PROGRESS TOWARD ASSIMILATION OF TOVS RADIANCES IN CANADA

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1. INTRODUCTION

Two projects aimed at improving the assimilation of TOVS data into NWP products from the Canadian Meteorological Centre (CMC) are currently under way. The first project is to modify the way NESDIS retrievals (SATEMs) are assimilated following the approach used at ECMWF (i.e. assimilating SATEMs as thicknesses over fairly thick layers following stringent quality control including a static stability check versus the model first guess). The focus of this project is on improving southern hemisphere analyses in the CMC global forecast/assimilation system. It is expected that this change will form part of a package of changes which CMC will begin testing in parallel this summer. The major element in the package is conversion of the operational optimal interpolation scheme to a three-dimensional box approach from the current vertical/horizontal split scheme.

The second project is aimed at assimilating raw TOVS radiances using a one-dimensional variational scheme (formerly known as non-linear optimal estimation) following the approach described by Eyre (1989). This project is focusing on data-sparse areas in the northern hemisphere, in particular the Pacific Ocean. We are currently using an archived global data set from February 1989 obtained through ECMWF. Progress on these projects has been slower than we had hoped due to other commitments and to the replacement of the CMC supercomputer and front ends. Some statistical comparisons of 1-D variational retrievals with collocated radiosondes have been done; these are shown in section 2. An experiment with specification of the guess temperature profile above the top level of the NWP model is discussed briefly in section 3. Following these comparisons we took another look at the problem of tuning the forward model for calculation of raw radiances. This is discussed in section 4.

2. COMPARISONS AGAINST RADIOSONDES

Raw radiance data from February 1989 obtained from ECMWF were used to produce 1-D variational retrievals at radiosonde sites in passive mode (i.e. the retrievals were not used to modify the model initial conditions to produce the first guess fields). The comparisons shown are for NOAA-10 from February 7-15 inclusive. The retrieval method was essentially unchanged from that described at ITSC-V (Steenbergen et al. 1989).

Figure 1 shows comparisons of the retrievals and the model first guess against radiosondes. The retrievals were done at the nearest TOVS pixel to the radiosonde location. The satellite measurements were within 2 hours of 00 and 12z. The statistics include all the matchups we obtained between 20N and 70N provided that
the elevation of the radiosonde site was less than 250 m.

Figs 1a and 1b compare the temperature retrievals with the first guess. The statistics are essentially the same between 850 hPa and 70 hPa. The retrievals show a modest improvement over the first guess above 70 hPa; however, the retrievals show larger bias and RMS difference than the first guess near the surface.

Figure 1c shows that the bias of the relative humidity retrievals (compared to radiosondes) is substantially smaller than that of the first guess. Figure 4d shows that the standard deviation of the relative humidity (retrievals - radiosonde) differences is essentially the same as for the first guess below 500 hPa, but is noticeably smaller in the vicinity of 400 hPa. This is consistent with the conclusion reached by Eyre (1993) regarding the potential of TOVS for upper tropospheric humidity.

3. SPECIFICATION OF UPPER STRATOSPHERIC TEMPERATURE FOR FORWARD CALCULATIONS

The top of the CMC spectral model was at 10 hPa in the configuration used for these experiments. Initially, temperature profiles between 10 hPa and 0.1 hPa were specified using statistical extrapolation as in the ITTP. Comparisons between observed brightness temperatures and brightness temperatures calculated from the first guess for HIRS channels 1-3 are shown in table 1. It can be seen that the bias and standard deviation for channel 1 in particular are very large, and that there is essentially no correlation between the brightness temperature calculated from the first guess and the observed brightness temperature for this channel.

To try to improve this situation, stratospheric temperature analyses were obtained from the NOAA Climatic Analysis Center at NMC. These analyses are done once daily for 8 pressure levels between 70 and 0.4 hPa (M. Gelman, private communication). The NMC analyses are done using a successive correction approach starting from the previous day’s analysis. Above 10 hPa the analyses rely almost exclusively on the NESDIS operational TOVS retrievals. The NESDIS retrievals use all three TOVS instruments; however, they depend heavily on SSU measurements above 10 hPa.

The comparison between observed brightness temperatures for HIRS channels 1-3 with values calculated from the NWP first guess is repeated in table 1(b). For these forward calculations, however, the statistically extrapolated temperature profiles above 10 hPa were replaced by values interpolated from the NMC analyses. It can be seen that the HIRS 1 correlation has increased to .77 and that the HIRS 1 standard deviation has decreased by more than 60% compared to table 1(a). Noticeable decreases in standard deviation and increases in correlation are also seen for HIRS 2 and 3. Although this comparison is not completely clean (since
the HIRS data were used in the NESDIS retrievals above 10 hPa) it illustrates the importance of the layer above 10 hPa in forward calculations for the more opaque TOVS channels. The retrievals used in the comparisons shown in the previous section used the NMC analyses for the temperature profile above 10 hPa.

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<thead>
<tr>
<th>Table 1. First guess vs observed brightness temperatures</th>
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<td>1a. Statistical extrapolation above 10 hPa</td>
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<td>1b. NMC analyses above 10 hPa</td>
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4. EMPIRICAL ADJUSTMENT OF RAW RADIANCES

A number of different methods have been used for empirical correction of HIRS radiances (e.g. Fleming et al. 1986, McMillin et al. 1989, Eyre 1992). Most of these techniques were developed for correction of cloud-cleared radiances which have been adjusted to nadir. Applying these techniques to raw (cloudy) radiances is complicated by the fact that there is insufficient independent information on cloud in the HIRS field-of-view to do forward radiative transfer calculations at the accuracy required. The retrieval of the cloud parameters depends on comparisons between observed and calculated radiances which contain the same systematic errors we are trying to remove. This circle of dependencies suggests the use of an iterative approach. As we envisage it, the loop includes three steps: (a) first guess information and observed raw radiances are used to retrieve cloud parameters; (b) the cloud parameters and first guess information are used to compute raw radiances; (c) differences between observed and computed radiances are used to modify empirical forward model tuning coefficients. The loop is repeated until a convergence criterion is satisfied.

In a 1-D variational retrieval using raw radiances the cloud fraction in the HIRS field-of-view, \( N \), and the cloud top pressure, \( P_c \), are retrieved simultaneously with increments to the temperature and humidity profiles and other variables. We cannot use the 1-D variational retrieval itself to retrieve \( N \) and \( P_c \) for radiance tuning because the retrieval maps differences between observed and
calculated radiances, which include the systematic errors we are trying to minimize, into changes in the temperature and humidity profiles as well as the cloud parameters. Consequently, we need to hold all inputs to the cloud retrieval algorithm except N and $p_c$ fixed but to otherwise make the cloud retrieval as compatible as possible with the 1-D variational scheme.

As a preliminary step, cloud parameters were retrieved by using only HIRS channels 7 and 8 and minimizing the sum of the squared differences between observed and calculated radiances. The retrieved cloud parameters were used to compute cloudy radiances for all channels which were compared to the observations. NOAA-11 passes over the Pacific within 2 hours of 00 and 12z from 10-15 February 1989 were used. The data were sorted into bins according to the retrieved cloud top pressure and cloud amount and mean differences between observed and calculated brightness temperatures were calculated for each bin. Examples of these results are shown in figure 2. Figures 2a and 2b show the mean differences between calculated and observed radiances for HIRS channel 5 as a function of retrieved cloud top pressure and cloud amount. Figure 2a is for daytime cases and figure 2b for night-time cases. Figures 2c and 2d show the same information for HIRS channel 19.

Figure 2a shows a trend towards more negative (observed minus calculated) mean brightness temperature differences with decreasing cloud top pressure up to 500 hPa with an increasing trend above 500 hPa. There is a noticeable diurnal effect for retrieved cloud top pressures greater than 950 hPa. Graphs for other channels such as 4 and 6 (not shown) are similar. These results are difficult to interpret but they seem to point toward systematic discrepancies between forward calculations for the more transparent channels which were used to retrieve the cloud parameters and the more opaque sounding channels. It should be noted that for these calculations no empirical optical depth adjustments were applied (i.e. $\gamma$ was set to 1 for all channels). It should also be noted that no attempt was made to identify clear cases other than allowing the retrieved cloud amount to go to zero or the cloud top pressure to go to the surface. This procedure should clearly be improved.

In these forward calculations we treated clouds as black (i.e. cloud emissivity was 1 for all channels). The large discrepancies between observed and calculated brightness temperatures seen in figure 2c (channel 19, daytime) show the expected increase in reflected solar radiation with increasing cloud amount and decreasing cloud top pressure. At night, we expected that calculated brightness temperatures for channel 19 should have been systematically warmer than the observed values. Figure 2d shows that this was not the case. This could be explained if retrieved cloud top pressures were systematically too small or retrieved cloud fractions were too large. This would occur if calculated brightness temperatures in channels 7 and/or 8 were too cold.
As the next step, we are attempting to include all the HIRS channels which see
cloud (or at least those which are not contaminated by solar radiation) in the
cloud retrieval and to weight them in a manner which is consistent with the
retrieval algorithm. Our proposed approach is described briefly below.

The retrieval minimizes a cost function given by

\[ J = (x - x_b)^T C^{-1} (x - x_b) + [y - y(x)]^T E^{-1} [y - y(x)] \]

where \( x \) is a vector containing all the elements to be retrieved, \( x_b \) contains the
a priori values of these elements, and \( C \) is the covariance matrix of the errors
in \( x_b \); \( y \) is the vector of observed radiances or brightness temperatures, \( y(x) \) is
a vector of expected values of \( y \) calculated from \( x \), and \( E = O + F \), where \( O \) is the
covariance matrix of measurement errors and \( F \) is the forward model error
covariance. If we wish to retrieve only \( N \) and \( p_c \) (i.e. to treat all the elements
of \( x \) except \( N \) and \( p_c \) as fixed at their background values) the first term in the
cost function effectively disappears.\(^1\) However, a new term appears in \( E \)
involving errors in the calculated brightness temperatures due to errors in the
elements of \( x \) which are being held fixed, i.e.

\[ E = KBK^T + O + F \]

where \( B \) is the error covariance matrix of all the elements of \( x_b \) except \( N \) and \( p_c \),
and \( K \) is the Jacobian of \( y \) with respect to these elements. It should be noted
that \( E \) depends on \( N \) and \( p_c \) through the dependence of \( K \) on these quantities.

We intend to adjust a small number of empirical forward model tuning coefficients
by minimizing a cost function given by

\[ J_T = \sum_j (R_j^o - \hat{R}_j^o)^T G^{-1} (R_j^o - \hat{R}_j^o) \]

where \( R_j^o \) is the vector of observed radiances for the \( j \)th member of a sample
which is representative of all cloud conditions and \( \hat{R}_j^o \) represents the
Corresponding vector of empirically adjusted calculated radiances. \( G \) is the
covariance matrix of \( (R_j^o - R_j^o) \), which can be estimated (for given values of the
cloud parameters) from \( B \), \( O \), \( F \), and \( K \). We are currently working on how the
minimization might be done.

\(^1\) For this purpose retaining the part involving the error covariance of
\( N \) and \( p_c \) does not appear to be useful.
5. PLANS FOR FURTHER WORK

Development of a three-dimensional variational assimilation system intended for the CMC was begun about a year ago. This project is being led by Dr. Pierre Gauthier. A prototype system is expected to be complete within the next year. Work towards assimilation of cloud-cleared radiances into the global model in the context of the 3D variational scheme will be our priority in the coming year. Work will also continue on validation and tuning of raw radiances along the lines described above as a step towards ultimate assimilation of radiances in this form.

6. REFERENCES


Eyre, J.R., 1992: A bias correction scheme for simulated TOVS brightness temperatures. ECMWF Tech. Memo. 186

Eyre, J.R., 1993: Applications of statistics between measured and forecast TOVS brightness temperatures, in this volume.


Figure 1: Retrieval - radiosonde differences (---) compared to first guess - radiosonde differences (-----).
A) Mean temperature differences
B) RMS temperature differences
C) Mean relative humidity differences
D) Standard deviation of relative humidity differences
Figure 2: Mean difference between observed and calculated brightness temperature as a function of cloud top pressure and amount for HIRS 5 & 19. Cloud amount curves are --- .1 to .2, -- -.3 to .4, ..-.5 to .6, ----.7 to .8, ----.9 to 1.
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