ATOVS Assimilation at UKMO

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1. INTRODUCTION

For many years TOVS and, since April 1999, ATOVS data have been assimilated for NWP at the U.K. Meteorological Office. Original use of the data was in the form of temperature products derived from the TOVS radiances by NESDIS (National Environmental Satellite Data Information Service, U.S.A.). These were assimilated into NWP in much the same way as are radiosonde temperatures.

One-dimensional variational analysis, 1D-Var (*Eyre 1989*), provides a more direct interface between the radiances and NWP. 1D-Var combines radiances with background temperatures and humidities from the latest NWP forecast to produce temperature and humidity profiles that in a statistical sense are optimal. These can be assimilated, as above, into a NWP system. This method was used operationally at UKMO for TOVS radiances from April 1996 until October 1999. It was found to result in improved NWP forecasts (*Gadd et al. 1994*). ATOVS radiances were included in April 1999, with substantial added benefit to forecast scores (*English et al. 1999a*).

Although assimilation of 1D-Var profiles would seem to be an improvement on the previous system, it is not an optimal use of the radiances. There is a theoretical disadvantage:

- The 1D-Var profiles contain information (and so errors) from the NWP model into which they are assimilated. Assimilation schemes typically assume that model and observation errors are uncorrelated.

There is also a practical disadvantage:

- This two-stage system (1D-Var and then assimilation) requires specification of radiance errors (for 1D-Var) and then 1D-Var profile errors (for assimilation). These must be tuned to optimise the system. Tuning requires running impact trials, and so tuning a two-stage system is expensive.

Development of a 3D-Var system at UKMO (*Lorenc 1995*) has provided the potential to assimilate the radiances directly. This use of the radiances avoids the disadvantages outlined above.

2. PRE-PROCESSING

All radiances are mapped to the HIRS instrument grid, so as to provide a full set of colocated microwave and infra-red radiances at each HIRS field-of-view. TOVS radiances are global 120km-resolution cloud-cleared radiances from NESDIS. ATOVS radiances are full-resolution data processed through AAPP (ATOVS and AVHRR Processing Package, *Klaes 1997*) from NESDIS global level 1b data.

Radiances judged to be affected by cloud are not used. Cloud detection for AMSU is performed within AAPP, as described in *English et al. 1997*. Cloud detection for HIRS makes use of the NWP model background and is described in *English et al. 1999b*.

3. 3D-VAR

3.1 Observation operator

Given an observation y_o, an observation operator $y(x)$ which maps NWP model state x into observed variables, and a combined observation and operator error covariance matrix R, 3D-Var can assimilate that observation (subject to $y(x)$ being differentiable and not too non-linear). 3D-Var seeks to minimise a cost function which measures fit of model state to model background and to observations. The observation part of the cost function for a single observation y_o is:

$$J_o(x) = \tfrac{1}{2}(y(x) - y_o)^T R^{-1}(y(x) - y_o) \tag{3.1}$$

and the gradient is

$$\frac{\partial J_o}{\partial x} = \frac{\partial y}{\partial x}^T R^{-1}(y - y_o) \tag{3.2}$$

To minimise the total cost function, 3D-Var requires values of J_o and the gradient $\partial J_o/\partial x$ at each iteration of the minimisation algorithm. Typically 3D-Var will iterate 40 times before convergence.

For TOVS and ATOVS radiances, the observation operator involves a radiative transfer model. The fast model RTTOV (*Saunders et al. 1999*) is used, in which calculation of optical depth has been parameterised for fixed layers of the atmosphere.

3.2 Reducing processing time

The calculations are CPU-intensive. Processing time can be reduced by calling RTTOV and its gradient routine RTTOVK only every 10^{th} iteration. The radiances y_1 and gradient matrix $\partial y_1/\partial x$ are calculated from model state x_1 for the first iteration and then stored. For iterations 2-10, with model states $\{x_n\}$ (n=2,...,10) the tangent linear approximation is used to estimate $y(x_n)$:

$$y_n = y_1 + \frac{\partial y_1}{\partial x}(x_n - x_1) \tag{3.3}$$

This process is repeated for iterations 11-20, etc.

3.3 Variables not analysed within 3D-Var

Several variables required by the radiative transfer model and analysed within 1D-Var are not analysed within 3D-Var. These are: temperature profile above the model top, surface skin temperature, surface emissivity and ozone. 1D-Var provides values for these.

3.4 Role of 1D-Var

1D-Var continues to perform a useful role. All available data on HIRS fields-of-view are processed in 1D-Var. As well as providing the variables for 3.3 above, it is used in monitoring the data, applying quality control, bias correction, and channel selection. It is followed by a thinning step which reduces the horizontal resolution of the data to one observation in each 2°x2° latitude/longitude box.

3.5 Choice of channels

An extensive set of criteria is used to determine which channels to use in what circumstances. These criteria are not described in full here, but instead the following gives a simplified picture of the channels used in 1D-Var.

HIRS: Over sea, when no cloud detected in the IR, channels 1-8 and 10-15. Otherwise channels 1-3 and 12. If high-level cloud is detected then 3 and 12 are also not used.

MSU: channels 2-4.

SSU: channels 1-3.

AMSU: Over sea, channels 4-14. Over land and sea-ice, channels 6-14. If cloud liquid water is detected then channels 4,5 are not used. If precipitation or scattering are detected then channels 6,7,8 are not used either.

At present, in the data-sparse land region 50°-70°N, 30°-130°E, we also use channels HIRS 4,5,6 and AMSU 4,5 when no cloud is detected.

The same channels are used in 3D-Var, except for the stratospheric channels HIRS 1, AMSU 12,13,14, and SSU, which are not used. The operational NWP model does not extend to the layers measured by these channels.

3.6 The wrong radiances

After initial trials were completed, it was discovered that due to a coding error 3D-Var was not using the observed radiances. Instead, it was using radiances calculated from the 1D-Var profiles, the 'retrieved' radiances. These radiances are neither the observed radiances nor the background radiances, but somewhere in between. For the microwave channels, where specified errors in R are small, the retrieved radiances are close to the observed. For the IR channels, where the specified errors are larger, the retrieved and observed radiances are not so close. Hence the radiances assimilated had information from the NWP background. The assumption continued within the assimilation that radiance and model errors are uncorrelated was still wrong. The system did have one advantage over assimilation of 1D-Var profiles. The profiles will contain fine-scale vertical structure from the background. The retrieved radiances do not resolve this structure (the 'null space').

4. Impact Trials

Assimilation of retrieved radiances was tested in two trials, using data from March and June 1999. The forecasts were verified against observations and also against the NWP analyses. Forecast scores were compared against those of a control run in which the 1D-Var profiles had been assimilated. Figure 1 shows 500hPa height anomaly correlation, verified against analysis, for the June trial. Small but consistent positive impacts are seen for 'Area 2' (Northern Atlantic) and the Northern Hemisphere. The Tropics also show a positive impact, although other variables show a mixed signal. The strongest signal is in the Southern Hemisphere, where impacts were strongly positive for all variables.

The June trial was rerun using the observed radiances. Impact relative to the assimilation of retrieved radiances was neutral when verified against analysis, but slightly positive verified against observations. Overall the impact against the control was very similar to that for the retrieved radiances, but with some improvement in the Southern Hemisphere.

5. Conclusions

Direct assimilation of radiances was found to perform significantly better than assimilation of 1D-Var profiles, as implemented at UKMO. Some of this may be due to the fact background information is no longer assimilated. However assimilating retrieved radiances, which do contain some background information, was almost as good as assimilating observed radiances. It may be significant that the fine-scale vertical structure in the background was not being assimilated.

Direct assimilation of radiances is a simpler system to tune than the two-stage 1D-Var/3D-Var system. This may account for some of the improvement gained through direct assimilation of radiances.

ACKNOWLEDGEMENTS

The author would like to thank and acknowledge the many colleagues involved in this work, in particular: S.J.English, A.J.Smith, T.J.Payne, A.J.Maycock, J.R.Eyre and A.C.Lorenc.

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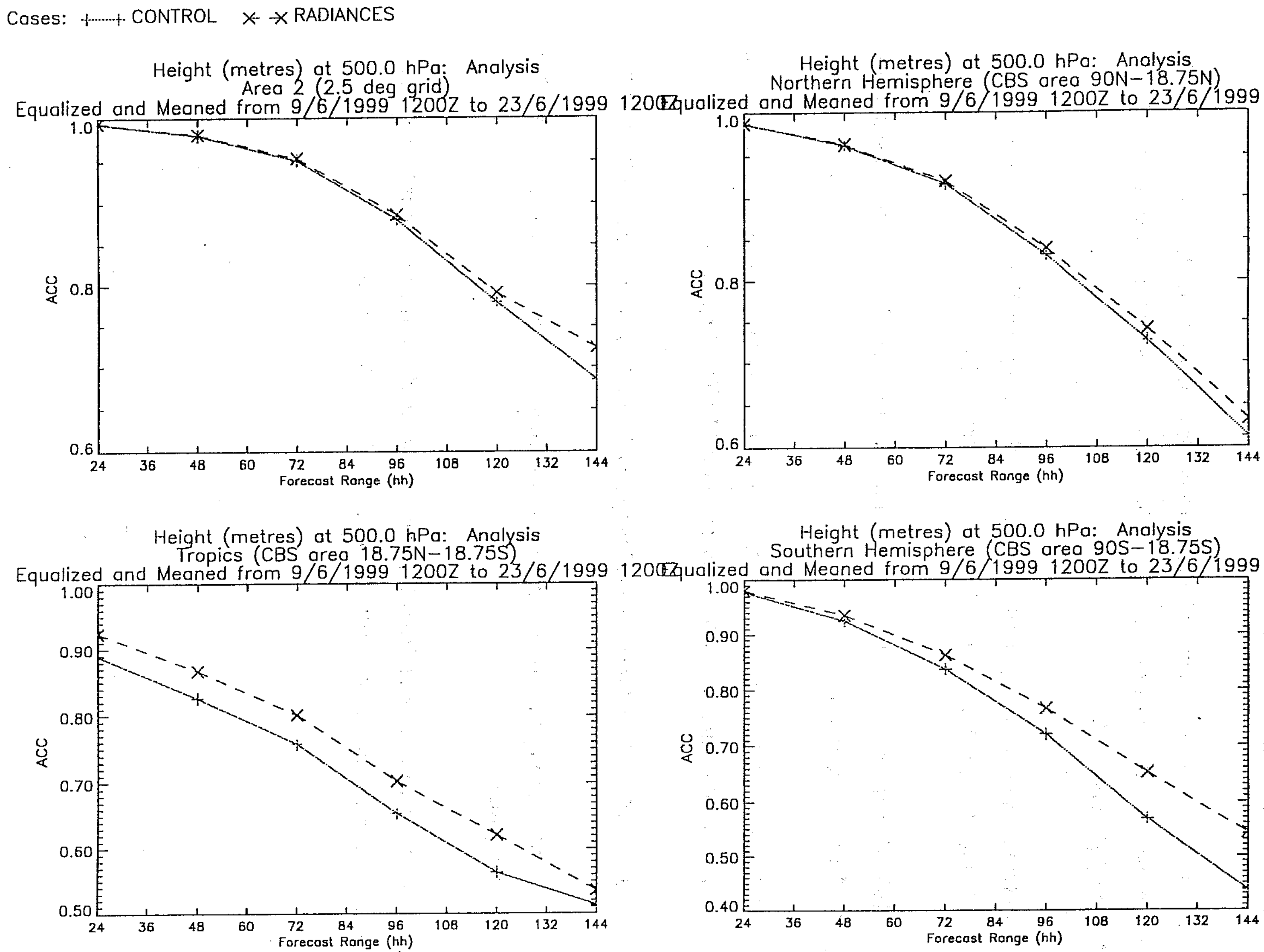

Figure 1: Anomaly correlation coefficient of 500hPa geopotential height calculated for four geographical areas from forecasts and analyses of two NWP trials: CONTROL (assimilating 1D-Var profiles) and RADIANCES (assimilating 1D-Var radiances). Area 2 is the N.Atlantic and N.W.Europe.