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THE CANADIAN 3D-VAR ANALYSIS SCHEME ON MODEL VERTICAL COORDINATE

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1. INTRODUCTION

The operational analysis system of the Canadian Meteorological Centre (CMC) has undergone major revisions in the last two years. The changes described in this paper are really a follow-up to the June 1997 implementation of the first Canadian 3D variational system (3D-var) described in Gauthier et al. 1999. First, in June 2000, 3D-var was converted from a 16-pressure to a 28 terrain-following-η level system (3D-Var-η) including a complete revision of background and observational errors. In this new formulation, there is an explicit balance constraint that is applied in the preconditioning for the minimization.

The first 3D-var was constructed to improve the assimilation of classical data and particularly to give us the ability to assimilate observations such as satellite radiances that are not directly linked to analysis variables. In September 2000, the use of satellite data was updated to directly assimilate TOVS radiances, in replacement of SATEM thickness data and this, as will be shown, has produced very significant improvements downstream of data void areas such as Western NA and in the SH.

Some years ago, the CMC developed unified model codes for both the global and regional forecast models (Côté et al. 1998). Similarly, the 3D-var system was also coded to support both the regional and global pressure systems as described in Gauthier et al. 1999, and Laroche et al. 1999. In January 2001, the regional spin-up system was fully upgraded from the 16 pressure levels to 28 terrain-following η levels including the direct assimilation of TOVS radiances as in the global analysis system.

2. EVOLUTION OF THE 3D-VAR IN THE LAST TWO YEARS; NEW STATISTICS, NEW SOURCES OF DATA, APPLICATIONS TO REGIONAL SYSTEM.

2.1 Formulation of the 3D-var, and estimation of new statistics

Several operational NWP centres currently employ, or have employed in the recent past, a 3D-Var system (Parrish and Derber, 1992; Courtier et al., 1998, Gauthier et al., 1999). Within a typical NWP system, the role of 3D-Var, like its predecessor 0I, is to produce the best estimate of the true atmospheric state by combining the current set of atmospheric observations with a short-term forecast (in this case a 6-h forecast, X_b) valid for the same time. The optimal estimate is the state vector, X, that minimises the cost function. 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. In this system, the penalty function that is minimized is,

$$J(\Delta X) = (\Delta X)^T B^{-1}(\Delta X) + (H'(\Delta X) - y')^T O^{-1}(H'(\Delta X) - y') \quad (1)$$

where H' is the linear observation operator linearized with respect to the short-term forecast and the increment ΔX, is defined as,

$$\Delta X = X - X_b \quad (2)$$

The initial misfit between the observations and the short-term forecast projected into observation space is defined as,

$$y' = y - H(X_b) \quad (3)$$

The innovations y' are computed in observation space using the full resolution background state X_b, whereas the analysis increments ΔX are calculated at lower resolution. In this study, the trial fields are used at the full resolution (0.9 degree grid) of the GEM model and the analysis increments ΔX are calculated at the lower T108 spectral resolution. The optimal estimate for 3D-Var is found by minimising the cost function (1) with an iterative optimisation algorithm employing the gradient of the cost function (the variational approach).

The 3D-var covariance statistics of the first pressure level system, like the previous 3D-OI system, were horizontally homogeneous and isotropic and separable. The covariance statistics of the 3D-Var-η system were redesigned following the approach of Parish and Derber (1992) based on an ensemble of 24 and 48-h forecasts valid at the same time. The 24-48-h forecast differences are not entirely representative of 6 hour forecast error statistics, and for this reason, the estimated variance fields are assumed to be zonally invariant and also must be scaled down using information from the variances of radiosonde observations minus forecasted wind and temperature averaged over broad latitude bands.

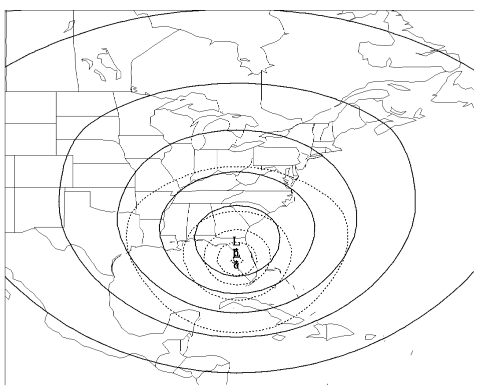

Fig. 1. Horizontal distribution of the analysed balanced increment (full) and unbalanced (dotted) at 258 hPa from one temperature datum at the same level. Units are Kelvin.

The cross-covariances between variables are related by simple geostrophic and the Ekman balances. The mass and wind variables are coupled by the operator,

$$\begin{bmatrix} \Delta T \\ \Delta p_s \end{bmatrix} = VL\Delta\psi + \begin{bmatrix} \Delta T' \\ \Delta p_s' \end{bmatrix} \qquad (4)$$

where the primes denote the "unbalanced" component of the variable, and the L and V are respectively the local geostrophic and the empirical hydrostatic inverse operators. The complete balance operator, is simply the product of the local value of the Coriolis parameter and the vertical operator V for reasons discussed in Gauthier et al. (1999). The linear operator V transforms vertical profiles of the balanced mass variable into temperature profiles. This operator is estimated using a regression analysis over the ensemble of error samples between temperature profiles and profiles of $L\Delta\psi$ in grid-point space. This approach is used to avoid problems of increased noise in the vertical structure and the null space associated with using a theoretically based inverse hydrostatic operator. Typically, one observation of temperature at 250 hPa would result in a horizontal and vertical spread such as indicated in Figs 1 and 2 respectively. As can be seen, even at latitudes as high as 30 N, the ratio of balanced to unbalanced is still high although the balanced flow spreads over horizontal scales much larger than the unbalanced component.

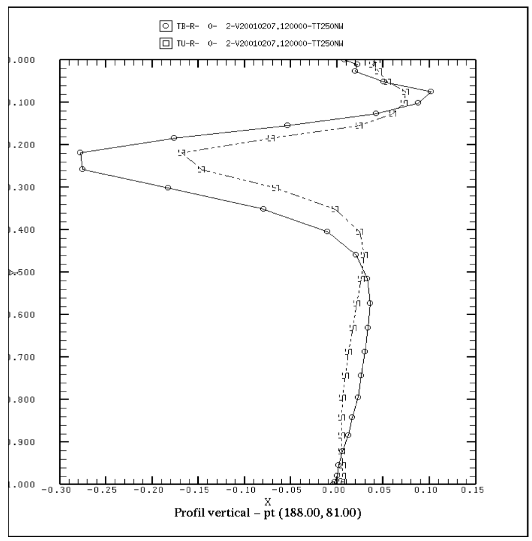

Fig 2. Vertical distribution of the balanced (full) and unbalanced (dotted) temperature increments resulting from one temperature datum at 258 hPa. Unit are Kelvin.

2.2 New sources of data; satellite and aircraft

2.2.1 Use of TOVS radiances: quality control, channel selection, and thinning

In 3D-Var-η, observations are assimilated in their raw or unprocessed form with the use of so-called "observation operators" thereby avoiding interpolating data to and from a fixed pressure grid prior to their assimilation. This is how we assimilated SATEM thicknesses in the previous 3D-var. In September 2000, the use of satellite sounding data was updated to directly assimilate so-called level-1d TOVS radiances (Reale and Chalfant, 1999) as a replacement for NESDIS-retrieved SATEM thickness. The direct use of radiances is accomplished with the help of a radiance transfer model (RTM), and for this study we used RTTOV-5 (Saunders *et al.*, 1999).

Following the launch of NOAA-15, it was evident that a new source of data had emerged that would alter the approach used at most NWP Centres in satellite data assimilation. The new AMSU-A microwave produced data of exceptional quality and appeared relatively easier to use than the IR data in all sky conditions. In this study, only the microwave data of NOAA-14 and 15 platforms are used. Only channels 6, 7, 8, 9, and 10 of AMSU-A from ATOVS and 2, 3, and 4 of the 4 MSU channels from the RTOVS system are used.

All radiances used are quality controlled prior to the monitoring and assimilation steps as described in Chouinard and Hallé (1997, 1999). A first series of checks involves validating the radiance data and its accompanying information. And finally, before the assimilation step, the data is thinned to a uniform resolution of 250 km.

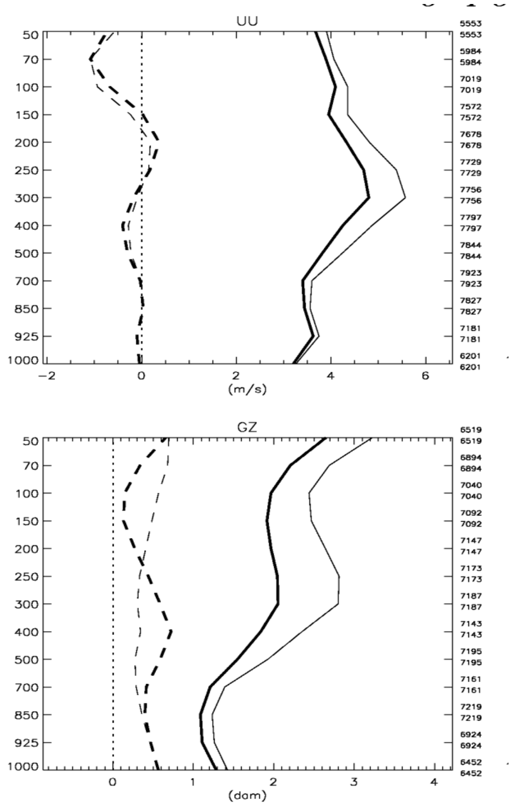

Fig 3. Wind and geopotential trial field evaluation against SH radiosondes with TOVS radiances (thick llines) and without the radiances (thin). The period of evaluation is 3 months. Units are m/s and dam.

The biases of the observed minus simulated radiances or innovations are carefully monitored in each channel so as to ensure that, over large ensembles (space and time, monthly global), they are very small, ideally zero. In some channels, the biases can be as large as -1 to -2 K and often as large as and even larger than the random error. These large biases have to be removed or accounted for if any success is to be obtained in assimilating radiance data. The bias correction procedure based on a two-step approach (Chouinard and Hallé, 1999) has recently been updated. In a first step, a global scan correction as obtained from prior monitoring is applied to the data; this removes most of the scan angle dependency. In a second step, the air mass dependent bias correction procedure using a set of regression equations for each radiance is applied.

The impact of TOVS radiances is very large and positive as indicated in Fig 3 which shows the improvements of the 6-h trial field in the SH when radiances are introduced.

2.2.2. Aircraft data: quality control, selection rules and thinning

In recent years, a very important source of wind data has become available in the form of automated aircraft wind reports (ACARS/AMDAR). The impact of these winds when added to the current operational AIREP data has been shown to be marginally negative in the 16-pressure level 3D-Var system and consequently was never implemented even though monitoring indicates the data is of very good quality. Because the correlation structures of the 3D-Var-η system are much improved, and because of its' improved vertical resolution, it was felt that the impact of the additional aircraft data would result in positive impacts particularly if accompanied by TOVS radiances.

CMC currently receives 4 different types of aircraft meteorological reports: AIREP, ACARS, AMDAR. In a 24-hour period, CMC receives approximately 45,000 ACARS, (US airlines data gathered by ARINC) 3,500 AIREP 20,000 AMDAR

Prior to their use in the analysis, the aircraft data are quality controlled. For the wind speed, a climatological test is performed. A separate quality control program is used for the basic quality assurance. TrackQC programs groups the reports according to the aircraft identifier and sort the observations chronologically and according to pressure level. The program does a quality control one aircraft at a time.

A background quality check is applied to remove the observations with gross errors before the data assimilation step. The decision to reject or not an observation is based on the square of the normalized background departure.

Finally, a data selection procedure reduces the density of the data while trying to make the best use of all the information available. At first, a 3-hour time window centred on the analysis time is used instead of 6 hours. Then, for each type of data, AIREP, ACARS and AMDAR, a thinning procedure is applied where a single observations is chosen in a 1.5 X 1.5 ° box on 16 pressure layers (1000, 950, 900, 850, 800, 750, 700, 600, 500, 400, 300, 275, 250, 225, 200, 150). When more than one observation of a given type is available, the one closest to the analysis time is retained. After the thinning, only one observation of the 3 types is kept prioritising in the following order: ACARS (1), AMDAR (2), and AIREP (3). This order is used simply because innovation statistics show that ACARS and AMDAR automated reports are on average of a better quality than the AIREP reports.

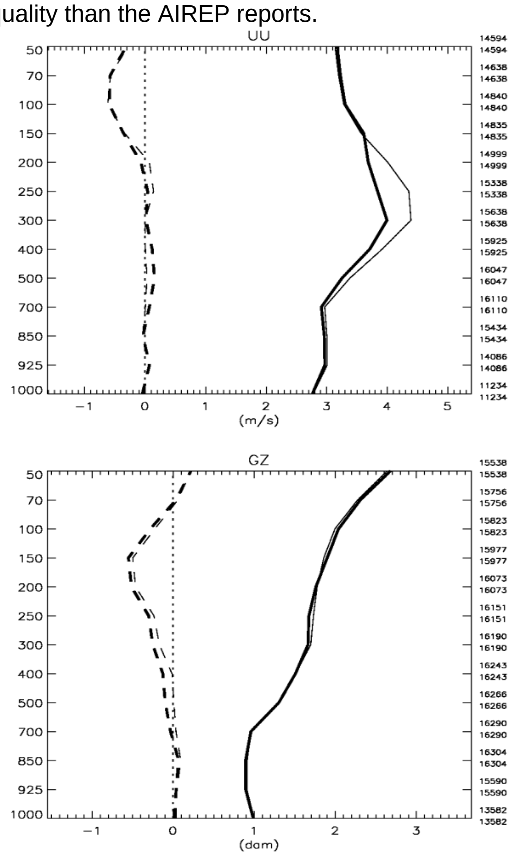

Fig 4. Wind and geopotential trial field evaluation against NA radiosondes with additional ACARS/AMDAR winds (thick llines) and without (thin). The period of evaluation is 3 months. Units are m/s and dam.

The added impact of ACARS/AMDAR wind data is very significant on the 6-h trial winds, and somewhat marginally positive on the geopotentials as indicated in Fig. 4.

2.3. Application to the regional analysis system

The 3D-Var-η system was, like its previous pressure system adapted to the regional model to produce analyses directly on model levels. Like in the global, the analysis increments are calculated at the low-resolution horizontal and vertical resolution of the analysis grid of the global statistics. The increments are interpolated to and from the regional model grid during the 12-h spin-up to arrive at the final analysis on the higher resolution regional model grid.

As expected, the same improvements obtained with the global 3D-Var-η were obtained in the regional system, but most significantly, the moisture analyses and the precipitation forecasts were significantly improved as shown in Fig 5.

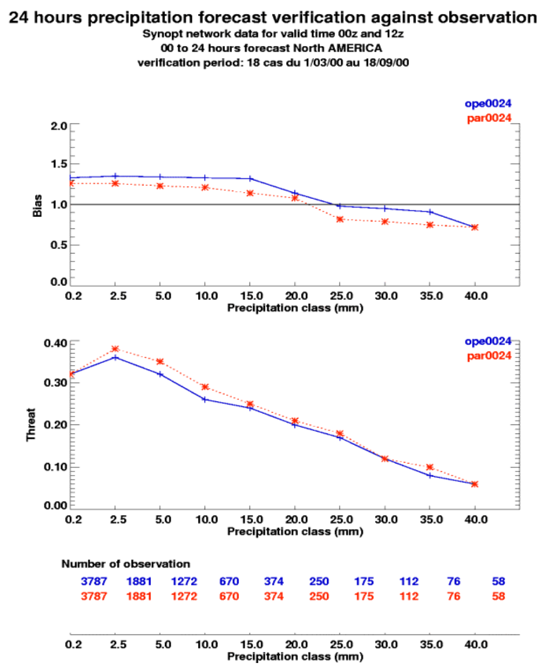

Fig 5. 24-hour QPF Bias (upper) and Threat Score (bottom) for the new regional 3D-Var-η system (dotted) evaluated against the 16-pressure level 3D-Var (full lines) for two periods in March and August 2000.

2.4. Direct assimilation of temperature (including significant levels) and surface pressure

Even though the analysed mass variables of the current 3D-Var-η regional and global systems are temperature and surface pressure, geopotential remains the main source of observations from RAOBS and similarly the surface pressure is assimilated indirectly as a proximity to surface geopotential datum. Because of this, significant level temperatures from RAOBS and aircraft temperature reports are not assimilated in the current system. Recently, we have introduced the direct assimilation of temperatures and surface pressure from RAOBS instead of geopotentials, and similarly, temperature and moisture observations from the surface synoptic meteorological (SM) network are now directly assimilated producing larger and more consistent corrections to the trial field thereby improving the surface and PBL structures.

Preliminary results shown (not shown) clearly indicate the positive impact of direct assimilation of surface and upper air temperature data on analyses and 10-day forecasts.

3. CONCLUSIONS AND FUTURE WORK

When TOVS/ATOVS microwave data are assimilated with aircraft wind data (ACARS/AMDAR) in the new CMC 3D-Var-η system, the two types of data support each other producing significantly better results then when either is assimilated separately. This was not the case in the previous pressure system where aircraft winds produced marginally negative results. This can only be attributed to the excellent quality of each data type and the improved 3D-Var-η data assimilation system, namely its statistics and balance constraints.

In preparation for the assimilation of satellite data from future platforms (NOAA-16, AIRS, IASI), we have started testing with level 1b TOVS radiances from current NOAA polar orbiters. The processing of radiances prior to the data assimilation step, including a revised bias correction algorithm based on NWP model air mass predictors, has been completely redesigned.

In the near future, temperature and surface pressure will replace geopotential observations and a variational quality control will be introduced within the minimization loop.

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