COMPARISON OF UKMO ANALYSIS CORRECTION AND 3DVAR DATA ASSIMILATION SYSTEMS

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1. INTRODUCTION

The UKMO has developed and is testing a 3D-VAR analysis scheme (*Lorenc*, 1996, *Ingleby et al*, 1996, *Barker et al*, 1996) which is planned to replace the current Analysis Correction (AC) Scheme (*Lorenc et al*, 1991) in the operational forecast system during 1999. The routine operational diagnostic monitoring systems are not currently available for trials of new or improved schemes so are not discussed in this paper. However information on the operational monitoring is available on the worldwide web at http://www.met-office.gov.uk/sec5/NWP/DA_Obsusage.html. This paper discusses the diagnostics used in the development and trials of the 3DVAR scheme.

2. DESCRIPTIONS OF 3DVAR SCHEME

The forecast model, the Unified Model, uses a B-grid in the horizontal and hybrid sigma-pressure levels on a Lorenz grid in the vertical. The analysis of increments is performed at coarser horizontal resolution on the grid staggering to be used for a new version of the model, ie C-grid in horizontal and the Charney-Phillips grid in the vertical where the wind levels match those of the full model. In the initial trials the forecast model used the old operational global resolution 288x217 and 19 levels. Once the operational model was using higher resolution 432x325 and 30 levels new trials were run. In both sets of trials 3D VAR used a 216x163 analysis grid with the same number of vertical levels as the forecast model.

The control variables used are increments of the streamfunction, velocity potential, 'unbalanced' pressure and relative humidity transformed to vertical modes and horizontal spectral coefficients. The 'unbalanced' pressure increment is defined as the difference between hydrostatic and geostrophic pressure increments. The geostrophic pressure increment is related to wind increments via a linear balance equation but is filtered vertically before use by carrying out a linear regression. This is to find a better approximation to the balanced pressure as the geostrophic approximation is a poor predictor in the tropics, at upper levels and near the surface as friction is currently neglected in the linear balance equation. The regression coefficients depend on latitude.

The background error correlations are calculated from the difference of a number of T+48 and T+24 forecast fields valid at the same time, (*Parrish and Derber*, 1992). The regression coefficients used for the filtered geostrophic pressure increments are also calculated from this data. EOF analysis of the global vertical correlations of the control variable parameters is used to calculate uncorrelated vertical error modes. Then horizontal power spectra are calculated for each vertical mode. The variance of each mode, ZNF, is treated as a function of latitude so that vertical covariances can vary with latitude.

Gravity wave activity in the forecasts, resulting partly from the need to interpolate the analysis increments from the analysis grid to the model grid, is controlled by using the Incremental Analysis Update (IAU) initialisation scheme, *Bloom et al* (1996). This scheme takes the increments to the background field, produced by the VAR analysis, and adds them on gradually to the evolving model fields every timestep from T-3 to T+3.

3. COMPARISON WITH THE ANALYSIS CORRECTION SCHEME

The formulation of the AC scheme is described in *Lorenc et al* (1991). It essentially performs an analysis with 1 iteration per model timestep and so combines the analysis, initialization and forecast in one process. Individual observations are included in the timestep analyses over a period T-4 to T+1 hours relative to the observation time. In contrast in the UKMO 3DVAR system the same observations in a 6 hour batch centred on the analysis time are currently all assumed to be valid at the same central time. A single analysis is performed and the minimization is iterated to convergence. These analysis increments are then nudged into the model forecast using the IAU.

Both systems use the same data sources and observation errors. Observations included are aircraft temperature and winds, TOVS 1DVAR retrievals of temperature and relative humidity, satellite cloud tracked winds, scatterometer winds, radiosonde temperature, relative humidity and winds, surface synoptic reports of pressure and surface wind over sea only. Most observations are pre-processed onto model variables, and in the case of radiosondes, levels for both schemes. In the AC scheme only 1/3rd of the TOVS data and 1/5th of the scatterometer data is used per timestep but all are used over 3 and 5 timesteps respectively. By default 3DVAR uses all the data in the analysis but there are options to pre-thin or reduce its weight.

The AC scheme uses background error correlations obtained from prescribed functions with specified radius of influence and vertical scale. For a given observation the horizontal correlation scale is time varying with a minimum at the observation time. The background error variances have synoptic dependence.

4. DIAGNOSIS OF BACKGROUND ERROR COVARIANCES

Two main methods are used to investigate the background errors in 3DVAR and compare them with the AC scheme. The first is to run single observation experiments ie run the analysis schemes with just one specified observation and study the analysis increments. The other is to study the forecast difference statistics used to calculate the background error covariances and compare them with the implied covariances resulting from using the background error covariance model in what is effectively a series of single observation analyses. Typically latitude/height sections of standard deviations and correlation with a given model level are compared for winds, stream function, velocity potential, temperature, relative humidity, pressure as well as the vertical modes and differential length scales as a function of model level and variable.

Initially the variational analysis gave implied temperature correlations that were too narrow in the vertical and the variances were too large near the top and bottom of the model so the multivariate linear regression to predict all levels of the original pressure p from all levels of Gp , referred to in section 2, was introduced.

For the 19 level model both horizontal and vertical scales implied by the forecast difference statistics seemed to be too large (compared to those used in the AC scheme and compared to the horizontal scales used in other centres). In the horizontal the original correlation spectra was replaced with those corresponding to Second Order AutoRegressive functions with the same differential length scales, CovSOAR; for the wind the kinetic energy scales were matched which seemed more reasonable than those for streamfunction and velocity potential. The streamfunction and velocity potential ZNF were rescaled so that the implied global kinetic energy is equal to that from the forecast differences. However this means that the balanced pressure variances are less than those from the forecast differences. These changes improved verification against analyses but verification against observations was slightly poorer. In particular they reduced the fit of the analysis to the observed tropical winds to that of the AC. The verification of the forecast tropical winds against the analysis improved dramatically but their verification against observations was poorer.

Streamfunction vertical correlations are broader than those for the wind components (u, v); when used in the variational analysis the implied vertical (u,v) correlations are slightly broader still giving excessive vertical length scales. To overcome this the streamfunction (velocity potential) vertical modes are replaced by those for Rotational (Divergent) Kinetic Energy. This has the desired effect of reducing the implied vertical scales. It also allows a better representation of the longer horizontal scales in the stratosphere. This improved the fit to observations and verification of forecasts against both analyses and observations, particularly the winds.

The initial trial defaults (CovSOARKE) included CovSOAR with rescaled variances and the use of KE vertical modes as described in the previous two paragraphs. These provided good results, in verification of forecasts, relative to the AC at low resolution. In order to improve VAR to match the AC at high resolution it was found beneficial to reduce the vertical scales further by a) scaling the ZNF of the first streamfunction mode by 0.9 (this has the longest vertical scale of the streamfunction modes) and b) an alternative form of rescaling to match the original kinetic energy (same scaling applied to all vertical modes rather than the default which is a mode by mode rescaling, this also implies slightly less weight to the first streamfunction mode but it also affects relative weightings of other modes). The combination of these two options is known as U1F9.

5. VERIFICATION AGAINST ANALYSES AND OBSERVATIONS

Continuous assimilation was run with analyses every 6 hours and 120hr forecasts every 24 hours. Two one week periods in January and July 1997 were run at low resolution and two 3 week periods in March and July/August 1998 at high resolution before starting a near real-time trial from late November 1998.

Improvements in global model NWP performance at the UKMO are judged on the basis of an "NWP index". this is a weighted sum of the skill, $S=1-r_i^2/p_i^2$ where r_i is the rms error with respect to analyses and p_i is the persistence error with respect to analyses, of key (customer related) forecast fields. In the northern and southern hemisphere these are T+24,48,72,96,120 mean sea level pressure, T+24,48,72 500hPa height and T+24 250hPa wind with the weights in the northern hemisphere being twice those for the southern hemisphere. In the tropics they are T+24,48,72 850hPa wind and T+24 250hPa wind. Highest weights are given to the short period forecasts. Therefore any studies of forecast performance will naturally concentrate on those fields.

However using verification against analyses as the means to judge whether the forecast system has been improved when changing the analysis component is tricky. Improvements in the "accuracy" (fit to observations and spreading of increments) and detail of the analysis could result in higher rms forecast errors. Therefore verification of analyses and forecasts against observations, particular the background fields at T+6, must also be monitored and verification of a fuller range of fields than just the components of the NWP index must be studied eg a wide range of pressure level temperature, height, relative humidity and wind fields and for the full range of forecast periods. It was found in the 3DVAR trials that skill measured against analyses could be very different to skill measured against observations. Fields verifying much better than AC against analyses, eg 50hPa temperatures, were actually those most degraded in verification against observations.

The CovSOARKE background errors were used for all 4 trial periods. At low resolution most "NWP index" fields were improved in 3DVAR compared with AC, in verification against observations and analyses, whereas at high resolution the skill of 3DVAR was generally slightly lower than the AC. This change in skill may have been as a result of the change of resolution but could also reflect the fact that different synoptic periods were used and that the high resolution trials also included the observation processing so that background fields for the TOVS 1DVAR retrievals came from the 3DVAR system for the 3DVAR trial. At both resolutions there was most significant improvement in the tropical winds compared with analyses, although in Jan 1997 and March 1998 the tropical winds verified worse than AC against observations.

The impact of modifications to the background error covariances, thinning of scatterometer wind data and TOVS retrievals and reduction of the weight given to the TOVS data on the performance of VAR was investigated. The AC scheme calculates its corrections in 2 stages:vertical then horizontal. The 1DVAR retrieval from TOVS is regarded as replacing the vertical stage, so the increments are only spread horizontally. In VAR a fully 3dimensional multivariate analysis is performed and there is strong correlation between upper level wind and temperature fields and the surface wind and pressure fields which is missing in the AC scheme. It is intended to move to direct assimilation of TOVS radiances so there is no allowance for vertical correlation of observation errors in the current version of 3DVAR. Instead the TOVS weight can be reduced by an empirically determined factor or the data can be pre-thinned.

A new configuration was selected for pre-operational, continuous, near-real time trials. This included CovSOARKE, U1F9 and pre-thinned TOVS data (about 2° resolution) . This improved verification against analyses and observations so that overall skill (ie NWP index) was similar for VAR and AC in March 1998 and better in VAR in July/August 1998 trials. Most components of the index improved slightly in verification against analyses but there was a more significant improvement in the T+24 wind components . The impact on verification against observations was less significant and tended to be negative for tropical winds. Additionally reducing the weight of the TOVS data further improved verification against analyses but degraded it against observations so that was not used. There was a negative impact from removing scatterometer data so that is not thinned.

For this final configuration in both the March and July 1998 trials the tropical winds are still the most significant improvement in verification against analyses of the NWP index components. In verification against analyses the T+24 pmsl and height verification for the winter hemisphere is slightly worse in 3DVAR but verification of these fields improves relative to AC with increased forecast range. Skill in the southern hemisphere fields is generally slightly worse in 3DVAR. In verification against observations just over half the NWP index fields verify better in VAR. To T+72 the pmsl verifies better than the AC in the southern hemisphere and is close in skill in the northern hemisphere. The tropical winds are worse in forecasts from VAR apart from 850hPa winds in July/August. The 3DVAR analysis generally fits the observations (radiosondes and surface data) more closely than the AC scheme but the backgrounds are of more similar quality. The quality of the background temperature fields in the southern hemisphere and tropics is generally poorer in VAR. There is a better treatment of atmospheric tides in VAR.

6. BALANCE AND SPIN-UP

The balance and precipitation spin-up in the two systems has been investigated. The IAU effectively reduces the gravity wave activity (measured by global rms surface pressure tendency) in the forecasts to the level in forecasts without assimilation and those using the AC scheme. The AC scheme has a marked spin-up of global mean total precipitation rate during the assimilation period which is absent in the IAU scheme. Both have rates lower than from a forecast without assimilation but the values during the IAU are much closer to the "no assimilation" values. A forecast from an unitialised VAR analysis produces excessive precipitation in the first timestep and then the rates undershoot. By the end of the IAU and AC assimilation periods the rates in all 3 forecasts with analysis or assimilation are very similar and remain so throughout the forecast period with rates slightly lower than the "no assimilation" forecast.

7. COMMENTS

Most improvements to verification against the analyses have been made by reducing the correlation scales and reducing the amount or weight of the data all of which mean there is less impact from the data. In some instances this has been at the expense of the skill of verification against observations, but still remains comparable to or better than the AC scheme for most variables. Now that longer trials can be run it will be possible to investigate more diagnostics such as the fit to other observation types, the geographical distribution of errors, the impact of the observation pre-processing (eg decisions relating to differences in station height and model surface) and the impact of biases in the data. It should be possible to investigate the impact of longer correlation scales on the relative performance against analyses and observations (especially in the stratosphere) and consider longer term developments such as revising the control variables, introducing synoptically dependent backgound error structures through links with forecast sensitivity and geostrophic transforms, exploiting the ability to use observation operators more directly related to the observations such as radiances, include surface friction effects and refining the observation errors. One main difference between VAR and the AC scheme is the more multivariate nature of the analysis and the stronger vertical correlation in VAR which can lead to significant impact of upper level data on the mean sea level pressure and surface observations on jet level fields. More investigations are required to assess whether this is causing problems or an improvement. So far in parallel trials VAR is performing well compared with the AC.

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