PROGRESS REPORT ON THE DEVELOPMENT OF THE MM5 3DVAR SYSTEM

Dale Barker, Francois Vandenberghe, Wei Huang and Yong-Run Guo

MMM Division, National Center for Atmospheric Research,*
Boulder, Colorado

1. INTRODUCTION

The importance of accurate initial conditions to the success of a assimilation/forecast numerical weather prediction (NWP) system is well-known. The relative importance of forecast errors due to errors in initial conditions compared to other sources of error such as physical parametrizations, boundary conditions and forecast dynamics depends on a number of factors e.g. resolution, domain, data density, orography as well as the forecast product of interest. However, judging from the current/future-planned resources (computational and human) of both operational and research communities being devoted to data assimilation, better initial conditions are increasingly considered vital for a whole range of NWP applications.

In recent years, much effort has been spent in the development of variational data assimilation systems as the "next-generation" to replace the previously used schemes e.g. the Cressman (MM5), FDDA (MM5), optimum interpolation (OI - NCEP, ECMWF, HIRLAM, NRL, etc) and analysis correction (UKMO) algorithms.

The advantages of the variational approach to more traditional data assimilation techniques include

• Observations can easily be assimilated in their natural space, e.g. satellite radiances, without the need for independent retrieval prior to the assimilation step. This results in a consistent treatment of all observations and, as the observation errors are less correlated, practical simplifications to the analysis algorithm.

• Although other assimilation techniques (such as MM5's FDDA) allow for the use of asynoptic data, a fully four-dimensional (space/time) variational data assimilation system implicitly makes use of flow-dependent error covariances through the use of the forecast model's tangent linear (TL) model and its adjoint.

• The inclusion of both dynamical and physical processes in the TL-model leads to an analysis that is in some sense balanced.

Having expounded the advantages of variational data assimilation it is wise to also recognise its weaknesses. Although the variational analysis is frequently described as "optimal", this label is subject to a number of assumptions. Firstly, given both imperfect observations and prior (eg background) information as inputs to the assimilation system, the quality of the output analysis will depend crucially on the accuracy of their respective *errors*. The accurate specification of both observation and background error is a large subject in itself and one which is being studied at NCAR and many other establishments. Secondly, although the variational method allows for the inclusion of linearised dynamical/physical processes, in reality real errors in the NWP system may be highly nonlinear. This limits the usefulness of variational data assimilation, especially in the tropics and at the mesoscale. Again, more work is required to advance the subject in these areas.

Despite the above weaknesses, the use of variational methods has been a powerful tool in the improvement of operational weather forecasts at a number of operational centres. The list of operational centres running three-dimensional variational data assimilation (3DVAR) systems grows every year. Following the first operational 3DVAR at NCEP (Parrish & Derber, 1992), other centres have followed with variants of the basic 3DVAR algorithm - ECMWF (1996), CMC (1997), DAO (1997), Meteo-France (1998), NCEP Eta(1998), UKMO (1999), FSL(2000) and NRL(2000).

Although 3DVAR is theoretically equivalent to OI (Lorenc, 1986), improvements over operational OI systems have been possible due to the removal of certain practical limitation of the OI approach. For example, 3DVAR assimilates all observations simultaneously (in OI a "data selection" algorithm is required to split the problem up into computationally affordable sub-problems). Also, the model-space 3DVAR algorithm allows for the speedy inclusion of new observation types

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Dr. Dale M. Barker, MMM Division, NCAR, P.O. Box 3000, Boulder, CO 80307-3000.

leading to a rapid improvement of developing 3DVAR systems over the more cumbersome OI algorithm.

In the development of variational data assimilation systems at the operational centres, 3DVAR has been seen as a necessary prerequisite to the ultimate goal of four-dimensional (eg 4DVAR/Kalman-filter-type) assimilation algorithms. The initial concentration on operational 3DVAR is partly motivated by the current lack of computing resources at most operational centres (with the exception of ECMWF) to run 4DVAR operationally. Without the cut-off time restrictions of the weather centres, the research community has tended to bypass 3DVAR and concentrate on applications of 4DVAR to new/asynoptic data types e.g. doppler radar.

Given the short-term (1-2 year) goal of designing a variational data assimilation system for operational use at AFWA and for Taiwan's Civil Aviation Authority (CAA), the plan for MM5 data assimilation is to initially concentrate on producing a respectable (*i.e.* accurate, computationally efficient and robust) 3DVAR system. The reasons for this are not just due to the computational resource issue of running 4DVAR but also

- Many of the algorithms used in 4DVAR are found in the much less computationally expensive 3DVAR system (eg observation operators, minimisation, preconditioning, multivariate, background error specification, data assimilation diagnostics). The only notable exceptions are the TL and adjoint of the forecast model, required for 4DVAR. The 3DVAR system therefore provides a training ground for these crucial aspects of the data assimilation system.
- There are still many potential ways of improving existing 3DVAR systems without the need for 4DVAR (although it must be considered for the proper use of asynoptical data). These include new observation types, improved specification of background/observation errors and improved balance constraints. These methods are sometimes referred to as "low-hanging fruit" in that they are sometimes computationally very cheap and also there is (and will be for the considerable future) much observational data that is under-used or ignored completely.
- Previous 3/4DVAR systems have been initially developed for the global assimilation problem. It is prudent to consider the particular aspects of the mesoscale (eg differing balance, impact of moisture, convection, etc) before following the path of other systems' development.

The layout of the rest of this report is as follows. In section 2. a summary of the features of the current MM5 3DVAR system is given including some results of recent tests. Finally, future plans for NCAR-MMM/MM5's data assimilation efforts are briefly described in section 3.

2. THE MM5 3DVAR SYSTEM

The goal of variational data assimilation is to find the analysis $\mathbf{x}$ which minimises the cost function

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}^b - \mathbf{x})^T \mathbf{B}^{-1}(\mathbf{x}^b - \mathbf{x}) + \frac{1}{2}(\mathbf{y}^o - \mathbf{y})^T(\mathbf{E} + \mathbf{F})^{-1}(\mathbf{y}^o - \mathbf{y}) \quad (1).$$

The various sources of information are the background vector $\mathbf{x}^b$ and its error covariance matrix $\mathbf{B}$, the observation vector $\mathbf{y}^o$, the observation instrument $\mathbf{E}$ error and the error $\mathbf{F}$ associated with the observation operator H which transform between analysis and observation space $\mathbf{y} = H\mathbf{x}$.

The fundamental equations of variational data assimilation have been written down many times in previous works (e.g. Lorenc 1986, Courtier *et al.* 1994). Here we suffice to summarise the particular features of the MM5 3DVAR system

- We choose to perform the cost function minimisation in terms of analysis increments $\mathbf{w}'$. This reduces any residual imbalance introduced in 3DVAR to the (small) increments: the output analysis is $\mathbf{x}^a = \mathbf{x}^b + I\mathbf{w}'$ where I is an operator which may include initialisation, change of grid, variable etc.
- The analysis is currently performed on the full MM5 forecast grid (Arakawa-B grid and sigma-height system of the non-hydrostatic MM5V3). Increments are constrained to be hydrostatic.
- The 3DVAR analysis domain is slightly larger than that of the subsequent MM5 forecast. This allows the use of observations slightly outside the forecast domain to be used to improve the lateral boundaries (if the background originates from an extended area e.g. a low resolution global analysis). The number of extra gridpoints is also chosen to alow efficient use of Fast Fourier transforms (FFTs) in the solution of the balance equation.
- Observation types currently assimilated include surface, radiosondes, aircraft, satellite cloud track winds and TOVS temperature and ground-based GPS total precipitable water retrievals.
- The incremental cost function minimisation is performed in "control variable" space $\mathbf{v}$. As well as improving preconditioning (which reduces the number of iterations taken for convergence of the minimisation algorithm), the elements of the $\mathbf{v}$ vector are chosen to reduce the background error covariance matrix $\mathbf{B}$ to diagonal form thus reducing the number of calculations required to feasible levels.

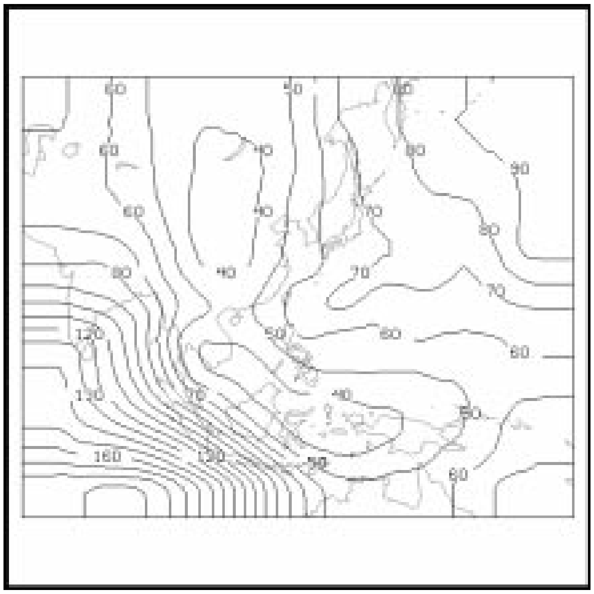

Figure 1: Example 'NMC'-statistics - the top level streamfunction σ_b (x10^{-5}m^{2}s^{-1}) for the Taiwan CAA MM5 Domain 1.

• The transform from control to model variables $\mathbf{w}' = U\mathbf{v}$ includes a conversion between model variables (u, v, etc) and approximately uncorrelated variables (currently streamfunction, velocity potential, unbalanced pressure and specific humidity).

• The background error covariances currently used in 3DVAR are derived from averaged T+24 minus T+12 forecast differences valid at the same time. This so-called 'NMC-method' provides an estimate of the climatological component of background error. In this study, the forecasts are taken from the real-time MM5 system running in Taiwan. An example plot of the streamfunction background error standard deviation σ_b field on the top model level (100hPa) is shown in figure (1). The figure illustrates the general variation of background error standard deviation over the domain as represented by the averaged T+24 minus T+12 forecast differences. The domain in figure (1) is that of the extended (see above) Taiwan CAA MM5 Domain 1 (resolution 135km). Boundary MM5 forecast domain σ_b values are used in the analysis domain extension zones, hence the kinks in the contours at the positions of the lateral boundaries of the inner forecast domain. The peak value in the lower left area of the box has been found due to large averaged differences in transverse wind component at the boundary between the 12 and 24 hour forecasts. Whether this truly represents background error or is an artifact of the use of the "NMC-method" to represent actual T+06 errors will be a component of a future study into the limitations of the NMC-method.

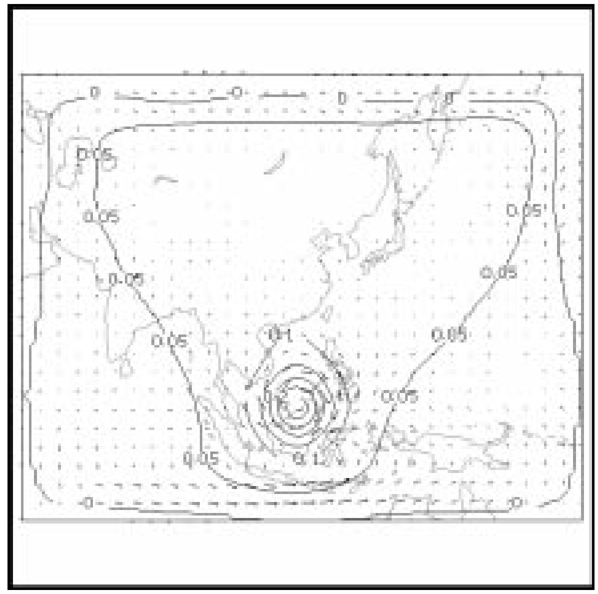

Figure 2: Test analysis increment response of 3DVAR to a single pressure observation.

• The MM5 3DVAR system is multivariate: a linearised balance equation is used to derive a balanced pressure increment p_b from the wind increments vector $\mathbf{v}'$ via a 2D linearised geostrophic/cyclostrophic balance equation:

$$\nabla^2 p_b = -\nabla \cdot \left[\overline{\mathbf{v}} \cdot \nabla \mathbf{v}' + \mathbf{v}' \cdot \nabla \overline{\mathbf{v}} + f\mathbf{k} \times \mathbf{v}'\right] \quad (2)$$

The first two terms on the right-hand-side of (2) are the linearised cyclostrophic terms, the last term is the geostrophic term used in most other mass/wind multivariate 3DVAR systems. The cyclostrophic terms are included to allow some mass/wind balance in areas of significant curvature and in the tropics where $f \to 0$. The background field is used to supply the linearisation state wind field $\overline{\mathbf{v}}$.

Figure (2) illustrates the multivariate impact of the current MM5 3DVAR. A single pressure observation is introduced to 3DVAR. The resulting pressure/wind analysis increments at the level of the observation are shown. The clockwise motion around the positive pressure increment (maximum 0.31hPa at observation location) is as expected from geostrophic theory. The origin of the returning anticyclonic circulation to the south of the observation will be investigated in the near future. In addition, the background error correlation scales used in the recursive filter are currently empirically set to a specified number of gridpoints.

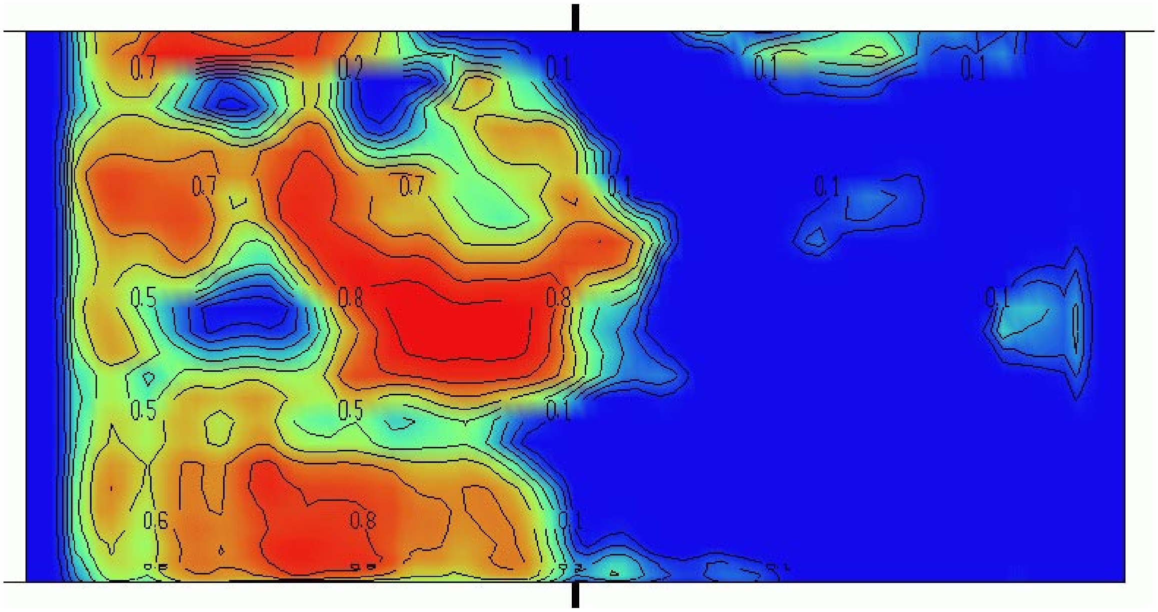

Figure 3: Averaged $< p_b p >$ correlation for the March 1999 forecast differences. Vertical axis is model level and horizontal axis is the (approximately) N-S of the Taiwan CAA domain 1. 'North' is at left and the equator is approximately located in the middle of the right hand half of the plot.

The arbitrary spreading of observation information in the current system leads to anomalous long distance correlations as seen in Figure (2). In the future, studies of the detailed dependence of lengthscale on variable, resolution etc. will be perfomed using the 'NMC'-method data to produce more realistic long-range increments.

A statistical study of the correlation between the balanced pressure - derived from the wind increments via (2) - and the actual pressure increment has been performed using the March 1999 T+24 minus T+12 forecast difference data. The $< p_b p >$ correlation from this data, averaged over the E-W direction as well as time is shown in Figure (3). Although the domain includes a significant area in the tropics, the presence of areas of large correlation (maximum $< p_b p >= 0.97$) indicates that equation (2) is a valid approximation to the true mass/wind balance in certain areas of the domain.

• The U transform includes a component projecting between variables on model levels and (orthogonal) eigenvectors of "global" vertical empirical orthogonal functions (EOFs). This is performed to reduce the vertical component of **B** to diagonal form.

• Horizontal background error correlations are represented using an isotropic and homogeneous recursive filter supplied by Jim Purser (NCEP).

• An off-the-shelf quasi-Newton minimisation algorithm is used to find the minimum of the cost function.

3. FUTURE WORK

The development of the MM5 3DVAR system to include the above features has continued at a fast pace since the freezing of an initial univariate version of the code in December 1999. Although the system is now multivariate and features three-dimensional background error correlations there remains significant work to do before the code is ready for general release to the MM5 user community. The current system MM5 3DVAR (System 2.0) is to be released in June 2000 to AFWA and CAA collaborators to enable them to perform initial experiments.

It is intended to release an updated version of MM5 3DVAR (System 3.0) in December 2000. Improvements to be included in this release, which will be made available to a wider group of users include

• Update of observation error characteristics.

• Initial work on porting MM5 3DVAR to MPP machines.

• Coding of additional observation operators eg SSM/I.

• Improvements to the preconditioning of 3DVAR.

• Improvements to the specification of background errors.

A particular longer term (2-5 years) goal for NCAR-MMM's data assimilation efforts is continual involvement in the WRF model collaborative effort between NCAR, NCEP, FSL, CAPS, AFWA and the research community to provide a next-generation assimilation/forecast system for both research and operational communities. With this in mind, the MM5 3DVAR system is being coded in as flexible a manner as possible to allow aspects of the MM5 to be used within the WRF data assimilation system.

REFERENCES

Courtier, P., Thepaut, J.-N. and Hollingsworth, A., 1994: *A Strategy For Operational Implementation of 4D-VAR, Using An Incremental Approach. Quart. J. Roy. Meteor. Soc.*, , **120**, 1389-1408.

Lorenc, A.C., 1986: *Analysis Methods For Numerical Weather Prediction. Quart. J. Roy. Meteor. Soc.*, , **112**, 1177-1194.

Parrish, D.F. and Derber, J.C, 1992: *The National Meteorological Center's Spectral Statistical Interpolation Analysis System. Mon. Wea. Rev.*, **120**, 1747-1763.