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THE WRF 3D-VAR ANALYSIS SYSTEM

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1. INTRODUCTION

The Weather Research and Forecasting (WRF) Modeling System is a cooperative program between NCAR, FSL, OU, NCEP, AFWA with contributions from other organizations to develop the next generation multiscale prediction system. A description of this project can be found on the WRF web page (http://wrf-model.org/) or in Michalakes et al. (2000). As part of this prediction system, a three dimensional-variational (3D-VAR) assimilation system is being developed. Using the experience of the various participating scientists and organizations, a design of the 3D-VAR assimilation has been developed and the construction of the basic system begun. The assimilation system is being coded to run both on serial processors and to exploit massively parallel features available on a variety of larger computing platforms. One goal of the 3D-VAR is a capability of analyzing information from a wide range of conventional sources, together with satellite radiances, radar radial velocities and reflectivities and other remotely-sensed data. Another goal is to accommodate a geographical and/or flow dependence of scale and variance parameters of the background error covariances together with a specification of three-dimensional anisotropy in a general way. The design and coding pays attention to the different requirements of the intended users, who will include research meteorologists and operational forecasting centers.

The system is being developed in three major stages. First, a basic system is being developed which will have only the basic components of the system incorporated in a structure that will allow efficient parallel processing. This system is not intended to be state-of-the-art in all of its features and use of observations, but to have a structure which will allow the incorporation of new features and observations in a relatively straightforward manner. The development of this basic version is under way and is expected to be complete late this year. The second stage is the development of a research version of the system (expected to be completed by the end of 2002). This version will incorporate all of the current state-of-the-art techniques and all currently used observational data sets. Finally, an advanced version will be developed in which new techniques and new observational data sets are incorporated. It should be noted that the development of this 3D-VAR assimilation system will be done in collaboration with other WRF groups, especially the 4D-VAR analysis group and the data handling and archive groups.

This paper will concentrate on the current design and status of the basic system with some comments about future enhancements.

2. INPUT

The analysis is designed to receive observational data (filtered by instrument specific quality-control) in the WMO standard BUFR format, together with a gridded background field and a specification of all relevant observation and background statistics. Procedures will be developed to transform many other non-standard formats into BUFR. The formulation assumes that the errors of observations are uncorrelated. This is not a real restriction since, as shown in the preprint for this conference by Purser and Derber (2001), it is possible to partition the correlated and uncorrelated components of a general observational error and augment the vector of analysis components to include the correlated parts in such a way that the analysis scheme will effectively have uncorrelated measurement errors and thereby retain the structural simplicity that this assumption implies.

3. VARIATIONAL FORMULATION AND CONTROL VARIABLES

The initial release of the analysis is based on conventional variational principles (for example see Daley 1991). It involves the minimization of the

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cost function $\mathcal{L}_1(\boldsymbol{x})$, symbolically defined in terms of measurements $\boldsymbol{y}$ and model variables $\boldsymbol{x}$ as,

$$\mathcal{L}_1(\boldsymbol{x}) = \mathcal{L}_a(\boldsymbol{x}) + \mathcal{L}_y(\boldsymbol{x}), \tag{1}$$

with

$$2\mathcal{L}_a(\boldsymbol{x}) = (\boldsymbol{x} - \boldsymbol{x}^b)^T \boldsymbol{B}^{-1} (\boldsymbol{x} - \boldsymbol{x}^b), \tag{2}$$

and

$$2\mathcal{L}_y(\boldsymbol{x}) = (\boldsymbol{y} - \mathcal{H}(\boldsymbol{x}))^T \boldsymbol{R}^{-1} (\boldsymbol{y} - \mathcal{H}(\boldsymbol{x})). \tag{3}$$

where $\boldsymbol{x}$ is the analysis vector, $\boldsymbol{x}^b$ is the background field from the model forecast, $\boldsymbol{B}$ is the background error covariance, $\boldsymbol{R}$ is the observational error covariance, $\boldsymbol{y}$ is the observation vector, and $\mathcal{H}$ denotes the transformation (possibly nonlinear) of the analysis vector to the observation vector. Later versions of the analysis are expected to include a penalty term to suppress nonlinearly diagnosed imbalance, variational quality control and various physical and dynamical constraints, but in the basic version, the analysis scheme will involve minimal nonlinearity.

The analysis variables are chosen to simplify the specification of the background error covariance and to allow incorporation of balances and other relationships between the variables. Thus, the background covariance operators are designed to act on one gridded field at a time with the analysis becoming multivariate through the employment of balance operators within the $\mathcal{H}$ operator. To make this possible, the analysis variables are chosen to represent approximately the geostrophically 'balanced' and 'unbalanced' dynamical components, with distinct background error covariances relating (univariately) to each of these component fields. The balanced control variable is the stream-function. The unbalanced variables are velocity potential and unbalanced pressure and temperature. In the first release, the analysis fields will be hydrostatically balanced; this restriction may need to be reviewed in more advanced versions. In the initial release a single moisture variable will be analyzed – at present this is the mixing ratio q; later releases are expected to address the problem of characterizing clouds. Apart from the projection into balanced and unbalanced fields, the analysis control variables belong essentially to the model-space, with exactly the same vertical coordinate grid and a horizontally unstaggered grid formed from the model's mass points. The resolution of the analysis is therefore identical to that of the model.

4. COVARIANCE OPERATORS

In the basic version of the analysis, the analysis code will assume background covariance statistics that are horizontally isotropic and homogeneous. The covariance operators corresponding to $\boldsymbol{B}$ in (2) are synthesized by a self-adjoint adaptation of the method of 'recursive filtering' first proposed for use in analysis by Purser and McQuigg (1982) and more recently extended by Purser et al. (2001a) for applications to variational assimilation. The method is an efficient alternative to the iterative technique of Derber and Rosati (1989) by which approximately Gaussian convolution kernels can be constructed. Through linear superposition, more general covariances may be built up from these Gaussian basic profiles. In the research version of the analysis, we intend to incorporate some of the spatially adaptive and anisotropic covariance structures that the recent developments in recursive filtering techniques allow. For a discussion of these developments, we refer the reader to the preprints by Wu and Purser (2001) and Purser et al. (2001b) at this meeting.

5. OBSERVATIONS

The basic version of the analysis will concentrate on observations which are relatively straightforward to use. These observations include synoptic surface observations, ships, aircraft, rawindsondes, wind profilers and pilot balloons. In the advanced and later versions, more complex observation operators will be incorporated to allow the inclusion of satellite radiances, doppler radar data (winds and reflectivity), GPS precipitable water and GPS radio-occultation observations and other observation types. The inclusion of each observation will involve development of the appropriate quality control, specification of observational and forward model errors and appropriate diagnostic and monitoring tools.

6. MINIMIZATION ALGORITHMS

In order to accommodate these future refinements efficiently, it is desirable to relegate all but the strongest nonlinearity to an infrequent iteration of the minimization algorithm so that the computations of the inner iterations, which normally dominate the overall cost, are kept as simple as possible. This 'outer and inner' iteration structure is being built into the analysis at the outset.

Various standard algorithms are available for large-scale minimization (Gill et al. 1981) and, although the standard preconditioned conjugate gradient algorithm is arguably the simplest of these methods, others are more advantageous for cases where the nonlinearity is significant.

7. DISCUSSION

The first release of the WRF 3D-VAR code is expected to become available late this year (2001) but will be restricted to essentially a linear analysis based on homogeneous and isotropic background error statistics. A later release will enhance the capability of the scheme with the inclusion of fully adaptive spatially inhomogenous covariances with anisotropic features responsive both to dynamical features of the ambient meteorological flow and to variations in *previous* observational data density and quality that influence the quality and characteristic spatial scales of error in the forecast background field. We expect to introduce more sophisticated nonlinear balance at the later release. Many important data types are not likely to be accommodated by the scheduled date of the first release. These data, which include radar data and a great variety of satellite remotely sensed data, require considerable care in their processing in order to be made amenable to assimilation by a variational analysis scheme in a way that is both numerically efficient and robust. These are the areas where we expect to devote a large proportion of our efforts in the future.

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