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3DVAR ANALYSIS IN THE RAPID UPDATE CYCLE

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1. INTRODUCTION

The Rapid Update Cycle (RUC) is one of the operational forecast/assimilation systems running at the United States' National Centers for Environmental Prediction (NCEP). From a model/assimilation viewpoint, the most unique aspect of the RUC is its use of generalized vertical coordinate configured as an isentropic-sigma hybrid coordinate. The adaptive nature of this coordinate has implications for application of data assimilation techniques, as well as for the forecast model. Recently, a three-dimensional variational analysis (3DVAR) technique has been developed for application in the RUC system with a hybrid vertical coordinate. In this paper, we provide an overview of the RUC 3DVAR in hybrid vertical coordinates and describe how it is used in an operational numerical weather prediction setting.

The RUC is a regional analysis and forecast system, but is applied at NCEP for high-frequency mesoscale data assimilation and short-range forecasts (Benjamin et al. 2001). Its uses include applications requiring numerical forecasts of duration from 1-12 h, including aviation, severe weather, and public weather forecasting. The RUC data assimilation is performed hourly, with the previous 1-h forecast used as the background for each analysis. Thus, it uses a very high-frequency forward intermittent data assimilation. The 3DVAR analysis is the main topic of this paper and is described in subsequent sections.

2. CHARACTERISTICS OF THE 2001 VERSION OF THE RUC

In 2001, a new version of the RUC is being implemented with a 20-km horizontal resolution covering the continental United States, much of Canada and Mexico, and neighboring oceanic areas. In the RUC, the atmosphere is resolved vertically by a generalized vertical coordinate prescribed as a hybrid isentropic-sigma coordinate. This coordinate is described in detail by Bleck and Benjamin (1993), and is defined by a series of two constraints. Each vertical level is assigned a reference virtual potential temperature (θ_v), and is set as the isentropic level at this θ_v unless superseded by the other constraint. The second constraint is that the level must be separated by at least some pressure separation from the level below. This constraint starts with the lowest level being assigned at the terrain elevation and the surface pressure corresponding to that terrain level. The result of this two-constraint prescription is a hybrid coordinate that starts near the surface as a terrain-following coordinate, but evolves toward an isentropic coordinate at the reference θ_v levels somewhere in the lower to mid-troposphere (depending on the θ_v specification and the prescribed minimum pressure spacing).

In the 20 km version of the RUC, 50 vertical levels are used, with a top level now at 500 K. The minimum pressure spacing used in this version of the RUC is 2, 5, 8, 10, 15 hPa for the lowest 5 layers, and 15 hPa for the remaining layers above, up to 400 hPa. Above this pressure, minimum pressure spacing is allowed to be as low as 0.5 hPa. The algorithm prescribing this hybrid isentropic-sigma coordinate requires about 20 lines of code. Outside of this algorithm, both the RUC numerical prediction model (Bleck and Benjamin 1993) and analysis are completely configured in a generalized vertical coordinate. A different algorithm prescribing, for instance, a sigma-pressure vertical coordinate may be substituted for the current hybrid isentropic-sigma coordinate. Thus, the RUC coordinate is quasi-isentropic, but also includes very high vertical resolution near the surface, even in nearly adiabatic conditions such as a typical daytime mixed layer. Since the pressure of a given isentropic surface increases with warming, the effect of the RUC hybrid coordinate algorithm is that more terrain-following levels are found in warmer regions. This effect is considered to be beneficial,

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since boundary layers are typically deeper in warmer conditions.

The analysis variables in the RUC are listed in Table 1. Each of these variables may be modified by the RUC analysis, in some manner or another based on the influence of observations. The cloud variables may be modified from satellite-based observations of cloud-top pressure, as discussed by Kim and Benjamin (2001). The top-level soil temperature (out of a multilevel soil model) is modified in accordance with the analysis change (increment) of the surface θ_v . Other land-surface variables (e.g., multilevel volumetric soil moisture) are directly forecast by the RUC, but are not listed in Table 2 since they are not modified in the analysis as of this writing.

Table 1. Prognostic and analysis variables in the Rapid Update Cycle

Dynamic variables
θ_v - virtual potential temperature
p - pressure (Δp or pressure thickness is the prognostic variable in the RUC model)
u, v - horizontal wind components
Water-related variables
q_v - water vapor mixing ratio
q_c - cloud water mixing ratio
q_i - ice mixing ratio
q_r - rain mixing ratio
q_s - snow mixing ratio
q_g - graupel mixing ratio
N_i - No. concent. of ice particles
Soil-related variables
T - soil temperature

3. DATA PREPROCESSING FOR RUC 3DVAR ANALYSIS

The guiding principle behind preprocessing of the observational and forecast background data for the RUC analysis is to match in meaning, as nearly as possible, the observation with the background information. The goal is to calculate *observation innovations* (observation minus background differences) that reflect exactly the difference between matched observation and background information content. The same goal, viewed from the opposite perspective, is to eliminate differences in the location and meaning between the observation and the background value. The data preprocessing performed for the RUC is coordinate-independent, in keeping with the generalized vertical coordinate framework described in section 2. Below, we describe processing for each observation type (other than cloud-top pressure, Kim and Benjamin 2001) assimilated in the RUC 3DVAR.

First we discuss the time validity and representativeness of a RUC analysis, including the time window for observations to be used within a given analysis. A RUC analysis is, in fact, not valid at a strict minute in time, but is valid from 15-30 minutes before its labeled valid time. Although not generally acknowledged, this is also true for other operational center objective analyses and model initializations. Rawinsonde balloons in the U.S. are launched about 45 min before the nominal observation time, and observations from these rawinsondes are made throughout the ascent of the balloon, with time matching the nominal observation time somewhere in the stratosphere. In the RUC, a 60-min time window for aircraft observations is used, centered on 30 min before the nominal analysis time. Wind profiler observations assimilated are hourly averages, also valid most nearly at 30 min before nominal analysis time. Surface METAR observations are made at about 15 min before each hour. For satellite observations ingested into the RUC, the time window is dependent on the analysis data cut-off time. In the current RUC with a data cut-off time of 20-40 min, assimilated satellite observations are generally from 15-90 min before the nominal analysis time.

3.1. Aircraft. Aircraft observations currently provide wind and temperature observations at a given pressure. Temperature observations are converted into θ_v observations using water vapor information from the background interpolated to the observation location. The wind observation is rotated to a grid-relative wind. In the RUC, background values of winds and θ_v are interpolated to the pressure of the aircraft report to provide observation residuals.

3.2. Cloud-drift winds. The preprocessing for cloud-drift winds is simple, with rotation to grid-relative winds and interpolation of background winds to the horizontal and vertical (in pressure) location of the observation to allow the calculation of the innovation

3.3. Surface observations. Of all in situ observation types, surface observations are perhaps most problematic for accurate calculation of innovations. This is primarily due to differences in elevation between these observations and the analysis and model terrain that can occur in mountainous regions. Over flat land areas or over oceans, this problem is less significant.

The RUC uses two primary techniques to refine surface observation residuals. First, observed temperatures and dewpoint temperatures are modified from their original values to values appropriate at the model elevation. Lapse rates over the lowest 25 mb from the model background are used for a modification of the observed surface temperature. In the RUC, this extrapolation of surface temperature is done only for station-minus-model surface pressure differences of less than 50 hPa. Obviously, the accuracy of this extrapolation is very dependent on the accuracy of the background thermal stability near the surface, and may be expected to be less accurate with greater extrapolation depth. The dewpoint temperature is modified such that the dewpoint depression (temperature minus dewpoint difference) is maintained as in the original observation, thus maintaining approximately the same degree of sub-saturation.

Second, a diagnostic routine using similarity theory in the surface layer is applied to low levels of the RUC forecast background to directly estimate temperature and dewpoint at a 2m height and winds at 10 m height, since these are the actual observation levels. Thus, the observation residuals for surface observations are applied at 2m for temperature/dewpoint and at 10m for winds. This 2/10 m diagnostic correction is applied even though there is a direct computational level at 5 m from the RUC forecast model, and has been found to be important in eliminating innovation biases varying over time of day.

Finally, there is a variable transformation for surface observations from temperature and dewpoint temperature to the corresponding analysis variables in the RUC, θ_v and q_v (water vapor mixing ratio).

3.4. Wind profiler observations. Under this type of observation, we include observations made in the United States from 405 MHz and 950 MHz (boundary-layer) profiler, and also velocity-azimuth display (VAD) vertical wind profiles made from radial velocity data from the national network of National Weather Service Doppler radars. Observations of wind are made at profile of discrete heights (gates) from all of these systems. The pre-processing for these observations is fairly simple, consisting of rotation of winds to grid-relative components and interpolation of background winds to the height of each profiler observation. No pseudo-observations are produced at interpolated heights between the original levels for these observations.

3.5. Rawinsonde observations. The unique aspects of RUC preprocessing for rawinsonde data concern the interpretation of significant level data and the treatment of near-surface structure. As with other types of observations, winds are rotated to grid-relative components, and temperature and dewpoint is transformed to θ_v and q_v. Both mandatory-level and significant-level data from rawinsondes are typically available to the RUC. Each of these levels are introduced directly to the RUC analysis. However, for rawinsondes with significant-level data only, pseudo-observations are also created at the levels corresponding to the vertical levels from the RUC background at the observation site. This procedure is performed since significant-level data are produced at inflection points from the high-resolution raw rawinsonde data as part of the data processing from the rawinsonde processing at each station. Thus, nearly linear profiles have been observed between significant levels in the raw data, but are not reported. The interpolated pseudo-observations between significant levels are designed to force the analysis to reflect this linear structure where observed.

3.6. Precipitable water observations. The 20km RUC assimilates integrated precipitable water observations available from both geostationary and polar-orbiting satellites. Innovations for precipitable water are calculated by differencing observations with model background data, including adjustments to account for elevation differences between the observation and model background.

4. ADAPTIVE 3-DIMENSIONAL ANALYSIS SPACE

The RUC 3DVAR analysis uses a generalized vertical coordinate configured in the hybrid isentropic-sigma coordinate described in section 2. The analysis solution is performed in an i/j/k space described below and in Table 2.

Table 2. Analysis output grid vs. internal analysis solution grid

	Horizontal Grid length	Number of vertical levels
Output grid	20 km	50
Solution grid	80 km	56

The 56-level solution grid for the RUC 3DVAR uses a more even isentropic spacing than the output grid, which uses much wider isentropic spacing in the stratosphere (up to 50 K) than in the troposphere (primarily 2 K). The 80-km analysis solution space is adequate given the current observation spacing in the RUC domain, and the 80-km 56-level analysis increment is interpolated back to the 20-km 50-level grid.

Some of the advantages of using a quasi-isentropic coordinate for atmospheric analysis are described by Benjamin (1989) and Benjamin et al. (1991). The influence of observations in correcting a background is adaptive depending on the 3D thermal structure in the vicinity of the observations. The extent of vertical influence is dependent on the separation in θ space, which is equivalent to a stability weighted pressure separation. From both of these effects, the influence of an observation tends to remain with the same air mass, as defined by the 3-D isentropic structure.

5. A DESCRIPTION OF THE RUC 3DVAR ANALYSIS SOLUTION

In the RUC 3dVAR, the standard form of the incremental variational cost function (Courtier et al. 1994)

$$J(\delta x) = (\delta x)^T B^{-1}(\delta x) + (\delta y_o - H(\delta x))^T R^{-1}(\delta y_o - H(\delta x))$$

is minimized. The vector variable δx contains all the incremental control variables: stream function (scaled by grid distance), velocity potential (scaled by grid distance), unbalanced height, virtual potential temperature (θ_v), and natural logarithm of water vapor mixing ratio. To obtain a more optimal analysis, the control variables differ from the analysis variables, which are wind (u and v components), height, virtual potential temperature, and specific humidity. Using the incremental approach, the analysis is of difference from the forecast background. During the preprocessing phase of 3DVAR, all observations are converted to innovations (difference from the 20-km background). No special superobservation procedure is applied in observation processing, but a simple observation density function is defined and applied in the analysis. There is no bias correction applied to observations or background fields.

Because one of our control variables is unbalanced height, we use the dynamics-generated coupling between the errors of height and streamfunction fields through the linear balance equation:

$$-\nabla(f\nabla\psi) + \nabla^2(gZ) = 0$$

Unbalanced mass is defined by the difference between the two terms in the balance equation. It is customary to convert the linear relationship generated by the linear balance equation into a linear regression relationship

$$\psi = L(Z) + \varepsilon$$

where the regression coefficients are computed using the NMC method (Parrish and Derber 1992). We use vertically different coefficients, which, after appropriate filtering, depend on geographical latitude only. The balancing relationship is applied in the height observation operator. It also helps to improve the conditioning of the 3DVAR minimizing equations.

The analysis space is the modified gridpoint (model) space described in section 4, with no staggering in the horizontal or vertical. Due to the grid-independent formulation of our scheme, it can be used for any 3D grid.

The analysis procedure is performed in three main steps (following the original optimum interpolation analysis design; see Benjamin, 1989):

1. Multivariate height/wind analysis where the rotational part comes from the coupled streamfunction and unbalanced height analysis and the divergent part is analyzed separately. (In this version, there is no coupling between the streamfunction and velocity potential fields; statistical analysis is under way to compute linear regression for near surface friction layers.)
2. The new height analysis is used to update the virtual potential temperature background field and new observation innovations are computed from this updated field. Based on these new innovations, a univariate analysis of virtual potential temperature is performed.
3. The final step consists of a univariate analysis of the moisture field.

Using the computed analysis increment fields, all background fields are updated at the end of the analysis process. In a postprocessing step, the analysis is adjusted to the hybrid isentropic-sigma coordinate by vertical interpolation back to nominal model levels as described in section 2.

The background error covariances are approximated by linear combinations of digital (pseudo-) Gaussian filters with different filter scales. The general form of a filter is

$$B = E^2 \sum w_i^2 G_i$$

where

$$\sum w_i^2 = 1$$

and

$$G_i = C_i C_i^T$$

and the C's are products of one-dimensional normalized Gaussian filters:

$$C_i = D_{ix} C_{ix} D_{iy} C_{iy} D_{iz} C_{iz}$$

where the D's are normalization (diagonal) matrices. E is the background error standard deviation, which is a function of the vertical coordinate and is adaptively computed from the values of preliminary statistics on pressure levels. In the present versions (40-km and 20-km) of 3DVAR, a filter package developed by R. James Purser at NCEP is used. (For further information and references, see Purser et al. 2001.) First order filters are applied both in forward and backward (adjoint) directions along the main axes (24 applications for one scan). For the time being, two length scales are involved in every complete (two scan) filter operation, which provides a resulting good approximation to the homogeneous and isotropic SOAR correlation functions applied in the former optimum interpolation method.

The minimization algorithm consists of a standard conjugate gradient method (Gill et al. 1981) specifically coded for RUC 3DVAR to guarantee effective computations. The full background error covariance matrix is applied in preconditioning (design following Derber and Rosati 1989). This preconditioning allows avoiding the impossible task of inverting background error covariance matrices. A decrease in the absolute value of the gradient of five orders of magnitude gives good convergence.

For most kinds of observations, the observation operators are linear interpolation operators. The precipitable water vapor operator is linearized around the most recent background and it is updated at every scan. To go from streamfunction and velocity potential to observed wind, finite differencing and linear interpolation is applied. The observation and representativeness error standard deviations are deduced from those used by optimum interpolation and computed adaptively according to analysis levels. In evaluation of the observational part of the cost function, the observation density function is used along the observation error standard deviations.

6. RESULTS

We will present examples of performance in the conference presentation.

7. ACKNOWLEDGMENTS

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