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This Technical Procedures Bulletin (TPB), written by Stanley G. Benjamin and Kevin J. Brundage, both of NOAA's Forecast Systems Laboratory, and Lauren L. Morone, of the Development Division of the National Meteorological Center, describes the Rapid Update Cycle (RUC).

The RUC is a mesoscale analysis/forecast system that operates on a 3-hour cycle to provide frequent and timely updates of tropospheric conditions and short-range (out to 12 hours) forecasts over the lower 48 United States and adjacent areas. It covers this area with a 60-km grid and has 25 isentropic-sigma levels on the native grid. The RUC has a unique position at the National Meteorological Center in that its analyses and forecasts will be available at frequent intervals in real time. To achieve this goal, the system was specifically designed to make use of automated aircraft reports and other asynoptic data such as profilers and surface data.

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The Rapid Update Cycle
Part I: Analysis/Model Description

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1. INTRODUCTION

During the late 1980s and early 1990s, there occurred a large increase in asynoptic meteorological observations over the United States, primarily due to the advent of widespread automated reporting from commercial aircraft and the implementation of a demonstration network of wind profilers. These new observations provided a database on which the time interval between three-dimensional analyses over this region could be reduced, for the first time, to less than 12 hours. A 3-h frequency analysis/forecast data assimilation system known as the Mesoscale Analysis and Prediction System (MAPS) (Benjamin et al., 1991,1993a,b) was developed by NOAA/ERL's Forecast Systems Laboratory (FSL) to take advantage of these new data. The first 3-h MAPS assimilation cycle began testing in late 1988 at FSL. Since that time, many significant improvements have been made, including increased resolution, more sophisticated analysis and modeling techniques, and the inclusion of new data types. In 1994, a version of MAPS software will become operational at the National Meteorological Center (NMC) as the Rapid Update Cycle (RUC), the latest of NMC's operational analysis/forecast systems.

The unique aspects of the Rapid Update Cycle are its use of high-frequency data assimilation and a vertical coordinate that is primarily isentropic. The RUC produces new three-dimensional analyses and short-range forecasts (out to 12 hours) every 3 hours (Figure 1). The analysis is based on a combination of observations (rawinsonde, aircraft, profiler, and surface) with a background field, usually from the previous 3-h RUC forecast. Thus, the RUC cycles on itself in a 3-h intermittent data assimilation cycle, explained in more detail in subsequent sections.

This Technical Procedures Bulletin presents detailed information about the RUC, including its domain analysis technique, and forecast model.

2. THE RAPID UPDATE CYCLE DOMAIN

2.1 Vertical domain - the hybrid-b isentropic-sigma coordinate

The Rapid Update Cycle uses a hybrid isentropic-sigma vertical coordinate in which most of the atmosphere is resolved with isentropic coordinates (defined as constant *virtual* potential temperature (θ_v) for the RUC), except for a layer near the ground where terrain-following (sigma) coordinates are used. For most of the domain, then, the RUC possesses the well-known advantages of isentropic (θ) coordinates in providing extra resolution in an adaptive manner near fronts and the tropopause. Some of the other advantages of isentropic coordinates in data assimilation include:

- Better use of observations in objective analysis -- The influence of the observations is extended along quasi-material θ surfaces along which advection occurs rather than the quasi-horizontal surfaces used with other vertical coordinates (e.g., Benjamin, 1989).

- Improved quality control -- Observations tend to appear more homogeneous on isentropic surfaces than quasi-horizontal surfaces.

- Improved forecast accuracy -- Vertical truncation error is virtually absent; three-dimensional advection becomes essentially two-dimensional in θ coordinates. Also, potential vorticity is better conserved, and precipitation spin-up in short-range forecasts is reduced (Johnson et al., 1993).

Since pure isentropic coordinates do not allow multilayer resolution of neutral or unstable boundary layers, a variety of hybrid isentropic-sigma coordinate techniques have been developed over the last two decades. However, the hybrid coordinate used in the Rapid Update Cycle is the only one with nonintersecting surfaces that retains θ-coordinate representation down to the lowest 1-2 km of the atmosphere regardless of baroclinity and terrain features. In the RUC hybrid-b coordinate, isentropic surfaces that approach the ground become terrain-following in a gradual manner, as shown in Figure 2. Each of the 25 RUC levels is assigned a reference virtual potential temperature (Table 1). The RUC surface follows the reference θ_v surface unless the surface falls within a prespecified pressure spacing of the ground. The prespecified pressure spacing, starting from the ground, is about 2, 5, 8, 10, and 15 mb, followed by as many 20-mb layers as are needed. In other words, the pressure of the RUC surface will be set equal to that of the reference θ unless that pressure is greater than that specified by the pressure spacing upward from the ground. This vertical placement is described in section 2.e of Bleck and Benjamin (1993). The prespecified thicknesses are reduced as terrain elevation increases upward from sea level. Higher terrain will usually result in more terrain-following levels since higher values of θ then occur closer to the ground. Note that more terrain-following levels stack up in warmer regions (e.g., the left/south end of the cross section in Figure 2) and in warmer seasons. This is another adaptive feature that coincides with typical planetary boundary-layer (PBL) depths since deeper PBLs are usually associated with higher values of θ in the PBL.

The RUC vertical coordinate is termed the "hybrid-b" coordinate since another hybrid coordinate (*with* intersecting surfaces) was tested in an earlier version of MAPS. More information about the hybrid-b coordinate may be found in Bleck and Benjamin (1993) and Bleck (1978). The hybrid-b coordinate was originally used in an ocean model (Bleck and Boudra, 1981).

The vertical resolution of the RUC is much greater than that of the 16-level Nested Grid Model (NGM) (Hoke et al., 1989) near the surface and in stable layers aloft, as shown in Figure 3. Again, the RUC resolution aloft is variable, depending on the local thermal structure. The Dayton, Ohio, profile shown in Figure 3 exhibits a very high, sharp tropopause where the RUC has three layers with less than 10-mb thickness. This can be compared with the coarser resolution at this level in the NGM. Compared to the 38-level Eta model (Black et al., 1993), the RUC has similar vertical resolution near the surface at sea level, but higher vertical resolution near the ground over elevated terrain regions. Aloft, it has much less resolution than the Eta model in layers of low static stability, but higher resolution near the tropopause and fronts.

For the RUC analysis and forecast model, there is no vertical staggering of the grid, meaning that all variables are defined on the same levels.

2.2 Horizontal domain

The current version of the Rapid Update Cycle covers the lower 48 United States and adjacent areas of Canada, Mexico, and oceanic areas with a 60-km grid (Figure 4). The mesh size is 81 by 62 grid points. A polar stereographic projection is used, with the sides of the domain parallel to 105° W. The 60-km grid length is true at 40° N; at 60° N, the grid length is 68.153 km. The lower left corner (grid point (1,1)) is located at 22.8373° N, 120.4905° W.

The terrain field used for the RUC, depicted in Figure 5, is an envelope topography field (equal to the mean plus standard deviation over grid box) taken from a 5-minute resolution topography data set. The envelope topography field is subjected to one smoothing and one desmoothing pass from the filter developed by Shapiro (1970). The maximum elevation is 3433 m (11263 ft) over central Colorado.

3. THE RAPID UPDATE CYCLE ANALYSIS

The RUC analysis is performed on the same horizontal and hybrid isentropic/sigma vertical grid described in Section 2. It calculates an analysis increment field, which is a correction that is added to a forecast background field, similar to the procedure used by analyses to initialize most operational forecast models. The analysis increment is computed by analyzing the observation residuals, which are the differences between observations and the background field interpolated to the observation points. The RUC analysis, then, is the sum of the background field and the analysis increment (correction) field. The background field for the RUC analysis is the previous 3-h forecast valid at the time of the current analysis. If the RUC assimilation cycle has been interrupted and the previous 3-h RUC forecast is not available, alternative background fields, such as NGM or older (≥6 h) RUC forecasts, may be used.

3.1 Analysis variables

There are six, three-dimensional variables analyzed by the RUC on the model coordinate, or native, hybrid-b surfaces. These variables are pressure (p), Montgomery stream function ($M = c_p T + gz$), virtual potential temperature (θ_v), condensation pressure (P_c, equivalent to the lifting condensation level), and the horizontal wind components relative to the grid (u and v). In the hybrid-b structure, θ_v usually will be constant for the top 6-12 hybrid coordinate surfaces, but this varies depending on the season. As described in Section 3.4, heights (z) are used in the RUC analysis, but the final output variable is M. P_c is currently used as the analyzed moisture variable because it is a conservative variable in the absence of evaporation or condensation and because it varies more linearly (e.g., from 100-1000 mb) than other conserved moisture variables such as specific humidity (e.g., from 20 - 0.01 g/kg with exponential variation). Byers (1938) discusses other advantages of condensation pressure over specific humidity for use on isentropic charts. However, as described in Section 4, mixing ratio is used as the water vapor moisture variable within the RUC forecast model.

3.2 Observational data used

Four types of observations are currently used in the Rapid Update Cycle: those provided by rawinsondes, commercial aircraft, wind profilers, and surface stations. The data cut-off for the current 3-h RUC is one hour and 20 minutes after the analysis time.

3.2.1 Rawinsonde

Rawinsonde data are usually available from 75-80 stations within the RUC domain twice daily, at 0000 and 1200 UTC. Asynoptic rawinsonde reports are also used in the RUC, when available. Rawinsonde data are converted to the RUC analysis variables described in Section 3.1. The full profile of mandatory- and significant-level data for all variables is then interpolated vertically to the levels (defined by pressure) of the hybrid-b background forecast. The background, in turn, is interpolated horizontally to the location of the station. For stations where the surface pressure is greater than the RUC background surface pressure (defined by the RUC terrain), this means that the lowest part of the sounding may be truncated and not used in the RUC analysis. This happens regularly at some stations in the western United States such as Grand Junction, Colorado (GJT) and Denver, Colorado (DEN). Only the interpolated data (up to 25 levels) are used in the RUC analysis. Heights are interpolated to these levels, as well as θ_v, P_c, u, and v.

3.2.2 Aircraft

The only aircraft data used in the RUC are those with automated digital reporting through ACARS (ARINC [Aeronautical Radio, Inc.] Communications, Addressing, and Reporting System). As of September 1994, about 12,000 ACARS reports per day were used in the RUC. The diurnal distribution of these aircraft data is dependent on the commercial route structure, and, therefore, has a strong diurnal variation (Figure 6). In addition, the number of reports decreases about 10% over weekends. ACARS reports provide winds and temperatures. The pressure is available from the reported flight level, which is a pressure altitude based on the U.S. Standard Atmosphere. Although θ can be calculated directly from the aircraft observation, moisture information from the background field is added to determine θ_v so that the aircraft temperature can be used directly in the RUC analysis of θ_v. More information about ACARS observations and their accuracy can be found in Benjamin et al. (1991), Brewster et al. (1989), and Schwartz and Benjamin (1994).

3.2.3 Profiler

Data from 26-28 wind profilers, mostly from the Wind Profiler Demonstration Network in the central United States, are available to the RUC as of September 1994. These profiles are interpolated to the pressure levels of the background forecast field at the observation point, as is done for rawinsonde profiles. The mapping from height (where raw wind profiler observations are defined) to pressure is performed with (p,z) data from the RUC background forecast. Only wind observations are currently available from profilers. Profiler quality control flags are examined at each raw data level, and only data that have passed a time-height single-station consistency check are passed to the RUC. More information on the accuracy and quality control of profiler winds is available in Weber et al. (1990), Martner et al. (1993), and Miller et al. (1994).

3.2.4 Surface

Observations from surface stations over land and buoys are used in the RUC. The data cut-off for surface data assimilated into the RUC is 35 minutes after analysis time, earlier than that used for the upper-air observations. The surface observations used in the RUC are initially processed in an hourly surface analysis cycle. Surface observations of z, P_c, u, and v are used. If the actual station pressure (calculated from the altimeter setting and station elevation) is more than 30 mb greater than the RUC surface pressure defined at the horizontal location of the station, the surface observation is not used in the RUC analysis because of inaccuracies in extrapolating the observations vertically. If this pressure difference is less than 30 mb, a height observation valid at the background surface pressure is determined by using a standard lapse rate and the observed surface pressure (e.g., a variation of Eq. (1) in Benjamin and Miller, 1990). A value for θ_v to be applied at the model surface pressure is also extrapolated via the standard lapse rate, and P_c is set so that the relative humidity is the same as in the original observation. The observed surface horizontal wind components are used directly.

3.3 Observation quality control

Considerable attention has been given to observation quality control for the RUC. An outline of the RUC quality control procedures is given below, but more detail may be found in Miller and Benjamin (1991). Three levels of observation quality control are used in the RUC:

- Platform reject lists,
- Gross error checks, and
- Buddy check against neighboring observations.

The first level of quality control (QC) in the RUC eliminates observations from platforms with known systematic errors. At this writing, platform reject lists are used only to eliminate observations from a small number of aircraft with reporting problems. A QC monitoring effort has begun to update the reject list for commercial aircraft on a monthly basis, if needed, to account for aircraft tail numbers with corrected problems or tail numbers with new problems (Moninger and Miller, 1994).

A series of gross error checks is then conducted. The most important of these are lapse rate checks and hydrostatic checks (the latter similar to that of Gandin, 1988) for rawinsonde profiles, and wind shear checks for profiles from both rawinsondes and profilers. For each of these checks, corrections to the profiles can be made in the event of inconsistencies.

A horizontal consistency or "buddy" check is then performed for the single-level observations and profile observations interpolated to hybrid-b levels. First, the background field interpolated to observation locations is subtracted from all observations to produce observation residuals. Then, surrounding observation residuals are interpolated to the location of each observation via univariate optimal interpolation. This "analyzed" residual, based on neighboring observations, is compared to the observed residual in question. If the difference exceeds a threshold based on expected random observation errors and a calculated analysis error, the observation is flagged as incorrect and not used in subsequent QC checks or in the RUC analysis. The buddy check for surface observations uses only other surface observations; the background for the surface QC is the previous hourly surface analysis from an hourly surface analysis cycle. More detail about the RUC buddy check and associated decision-making algorithms is given by Miller and Benjamin (1991).

3.4 Analysis procedures

The RUC performs a multivariate height/wind analysis and subsequent univariate analyses of θ_v and P_c, all using optimal interpolation. The multivariate analysis allows height observations to influence the wind analysis and wind observations to influence the height analysis. More detailed information on an earlier, pure isentropic analysis similar to the current RUC hybrid-b analysis is provided in Benjamin (1989).

In the following discussion, differences from the background, whether for observations (observation residuals) or for analyzed fields (analysis increments), are designated with the symbol ' .

As with the quality control, observation residuals are determined by subtracting the background field from all observations. First, the analysis increment is calculated for heights and winds in a z'/u'/v' multivariate analysis. The geostrophic coupling in the RUC analysis is relaxed by a factor of 0.5 at levels above the surface and further to 0.3 near the surface (Benjamin, 1989). This relatively small geostrophic coupling factor means that the RUC analysis increment is allowed to be fairly ageostrophic, especially near the ground, an appropriate procedure for a meso-alpha-scale analysis. Hydrostatic virtual temperature increments are calculated from z' to modify the θ_v field before a univariate θ_v analysis is performed. Thus, height observations are used in the RUC analysis multivariately, but their real effect is to help improve the temperature field. Both the z' and θ_v' analyses contribute to the final θ_v field. The output Montgomery stream function or geopotential height from the RUC analysis is determined by hydrostatically integrating the analyzed θ_v values in each column.

The condensation pressure (P_c) is also analyzed univariately. Horizontal distances, on which analysis weights are dependent, are modified dependent on wind flow and speed for the P_c analysis only, similar to the procedures of Benjamin and Seaman (1985) and DiMego (1988).

At this point, the fields no longer correspond exactly to isentropic surfaces, because the θ_v field itself has been changed. Therefore, an adjustment back to the hybrid-b surfaces is done as a last step. This adjustment is very similar to that performed at each time step in the RUC hybrid-b forecast model (Section 4.2). Note that before this final adjustment, the RUC analysis procedure is applicable to any vertical coordinate; the same techniques would be appropriate for a sigma-coordinate or isobaric analysis.

Single-level observations are allowed to influence multiple levels, and the vertical correlation of forecast error is prescribed as a function of potential temperature separation. This prescription is different from that of most other operational analyses, which typically use log-pressure separation. It results in a sharper cut-off of the influence of single-level observations near stable layers such as the tropopause. In the event of a rawinsonde "blow-off" (when the balloon is carried quickly downstream and the elevation angle becomes too small for accurate wind determination), the influence of the highest wind observation in the ascent is extended upward as if it were a single-level observation.

"Superobservations" are created in the RUC analysis by combining observations from similar platforms (e.g., aircraft) if they occur within 50 km of each other and are found in the same analysis layer. The purpose of this procedure is to use as much data as possible in the analysis and to eliminate the potential for nonpositive definite matrices in the optimal interpolation analysis solution. When observations are too close together in an optimal interpolation analysis, the result can be a poor analysis or even a program crash. The chief effect of creating superobservations in the RUC is to combine aircraft reports. If a pair of observations of different types is closer than the distance threshold, the observation type is used to select one or the other in the following order: rawinsonde, surface, profiler, and aircraft.

Observations are selected for 4X4 groups of grid points at each of the 25 levels. The observation selection algorithm locates the nearest observations in each of eight directional sectors, as shown by Benjamin (1989). In each of these sectors, the search algorithm attempts to find a profile observation (rawinsonde or profiler). If single-level observations are found closer to the grid points to be analyzed than the profile observation, they too are included in the analysis. Up to one single-level observation in the same analysis layer and one off-level single-level observation may be used. In total, there may be up to one profile observation (z, u, v) and one additional on-level and one off-level single-level observation (usually aircraft observations, each with u and v) for each of the eight sectors, giving a total of 56 observed values that may be used in a single multivariate analysis for a 4X4 group of horizontal grid points at a single level. The same algorithm is used for selecting observations for the univariate θ_v and P_c analyses.

Horizontal correlation of 3-h forecast errors is specified from a study of MAPS forecast errors by Carrière (1991). Forecast error standard deviations are also taken from Carrière, and observation error standard deviations are given by Benjamin (1989).

4. THE RAPID UPDATE CYCLE FORECAST MODEL

The Rapid Update Cycle forecast model is the generalized vertical coordinate model described by Bleck and Benjamin (1993). Modifications to a 20-line section of code in the model are sufficient to modify it from the hybrid-b coordinate described in Section 2.1 to either a pure sigma or pure isentropic model. More detailed information on the use of generalized vertical coordinates in geophysical models is given by Bleck (1978).

4.1 Prognostic variables

The primary prognostic variables in the current RUC model are pressure thickness between model levels, virtual potential temperature, water vapor mixing ratio, and horizontal wind components. Mixing ratio is converted to P_c for output at the current time.

4.2 Numerics

The Arakawa C grid (Arakawa and Lamb, 1977), in which u and v values are located on their own set of points offset from mass points to improve numerical accuracy, is used for the horizontal grid structure in the RUC model. There is no vertical staggering. The time step is 90 seconds at the current resolution. Positive definite advection schemes, which are very accurate and eliminate the possibility of negative values, are used for advection of pressure thickness (continuity equation) and for horizontal advection of θ_v and q (Smolarkiewicz (1983) with modifications described in Bleck and Benjamin (1993)). Adams-Bashforth time differencing (Gear, 1971) is used in the momentum equation with a forward-backward scheme for the Coriolis term.

The 20-line section of code that is unique to the hybrid-b coordinate occurs after the continuity (pressure thickness) equation is solved. At this point, the pressure at the reference θ_v levels (Table 1) is determined, and if it is less than the prescribed maximum pressure based on the surface pressure and minimum pressure thicknesses, the point remains on the isentropic surface. Otherwise, it is forced to be on a terrain-following surface, as shown in Figure 2, and its θ_v will not be equal to the reference θ_v value for that level.

Otherwise, the RUC hybrid-b model appears similar to a sigma-coordinate model. However, in the RUC model, vertical advection takes place only near the ground and in the isentropic part of the domain when there are diabatic processes such as latent heat release. Most of the three-dimensional motion as air ascends and descends is handled two-dimensionally in the RUC model.

4.3 Physical parameterizations

The hybrid-b RUC model contains the following physical parameterizations:

- Stable and convective (Grell, 1993) precipitation. Evaporation of precipitation occurs with convective precipitation but not with stable precipitation in the current RUC model.

- Turbulent mixing at all levels using the level 2 scheme of Mellor and Yamada (1982). More details on its implementation in the RUC model are given in Bleck and Benjamin (1993) and Pan et al. (1994).

- Surface fluxes of heat and moisture based on a surface energy budget including both shortwave and longwave radiation incident on the surface (Pan et al.,1994).

- Effects of interactive clouds (estimated fractionally from model-forecast relative humidity) on shortwave and longwave radiation.

4.4 Boundary conditions

4.4.1 Lateral boundary conditions

At this writing, lateral boundary conditions to the RUC are specified from the Nested Grid Model. NGM data at 6-h intervals with mandatory-level resolution and 80-km spacing are interpolated to the RUC hybrid-b vertical and horizontal grid. RUC forecasts are nudged each time step toward NGM values linearly interpolated in time according to the Davies (1976) scheme. The most recent NGM forecast available is used for RUC lateral boundary conditions. RUC forecasts initialized at 0000 and 1200 UTC use 12-h old boundary conditions, since the new NGM forecast is not completed at the time the RUC is run. Thus, a RUC 12-h forecast initialized at 0000 or 1200 UTC is nudged toward a 24-h NGM forecast valid at the same time on the boundaries. It is planned that the RUC will be changed to use boundary conditions from the Aviation model at a future time.

4.4.2 Lower boundary conditions

Surface characteristics such as albedo, soil moisture, and roughness length are allowed to vary horizontally and are specified as a function of climatology. There are 13 surface land-use types, and a value of each characteristic is specified for each one (Pan et al., 1994, Anthes et al., 1987).

The ground or sea-surface temperature in the RUC is currently set equal to the air temperature at the lowest level in the initial conditions. Until this deficiency is corrected (in the near future), the absence of accurate water temperatures means that RUC grids will typically be too dry in situations such as return southerly flow from the Gulf of Mexico.

4.4.3 Upper boundary conditions

There are no special procedures currently used for upper boundary conditions in the RUC.

4.5 Initialization

Before each RUC forecast begins, a forward/backward initialization procedure is applied within the model. The model is run adiabatically for 60 minutes in both the forward and backward directions. The values of mass and wind variables at each time step are averaged with weights specified from a digital filter to produce a more balanced initial state (Lynch and Hang, 1992). It has been found that application of this digital filter initialization considerably reduces gravity wave noise in the first few hours of RUC forecasts.

5. RAPID UPDATE CYCLE OUTPUT FIELDS

The hybrid-b grid structure and original variables used in the RUC are at least slightly unconventional. Therefore, output is converted to more familiar variables and vertical coordinates for users. In addition, the RUC delivers a number of useful two-dimensional fields not previously discussed. For each 3-h cycle, these fields are output as gridded data for the analysis and forecasts at 3, 6, 9, and 12 hours. The following sections describe the contents of files in GRIdded Binary (GRIB) format that are available for access on a network file server at NMC. The RUC model output is interpolated to GRIB grid #211, an 80-km, Lambert conformal projection. Those users now accessing specialized output for use with PCGRIDDS display software are expected to convert to the direct use of these GRIB files.

5.1 Isobaric fields

The RUC three-dimensional fields are interpolated to isobaric levels between 1000 and 100 mb with 25-mb resolution. The variables on these surfaces include temperature (rather than virtual temperature), heights, relative humidity, and horizontal (u and v) grid-relative wind components. Users accessing RUC gridded data via ISPAN will

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Level	Reference Isentropic Value
1	224 K
2	232 K
3	240 K
4	248 K
5	256 K
6	264 K
7	272 K
8	280 K
9	286 K
10	292 K
11	296 K
12	300 K
13	304 K
14	308 K
15	312 K
16	316 K
17	320 K
18	325 K
19	330 K
20	335 K
21	342 K
22	350 K
23	360 K
24	380 K
25	410 K

Table 1. The Rapid Update Cycle Reference Isentropic Levels

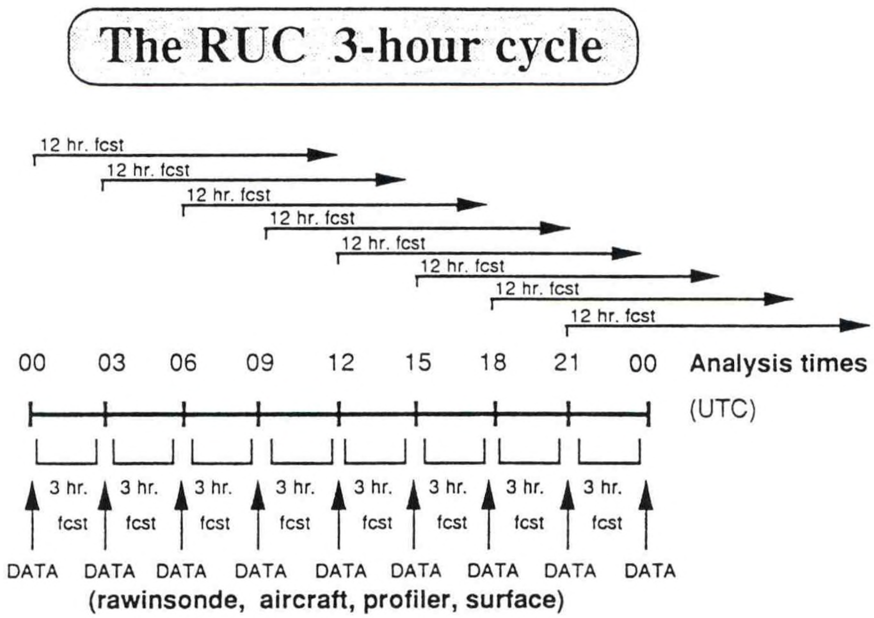

Figure 1. The Rapid Update Cycle

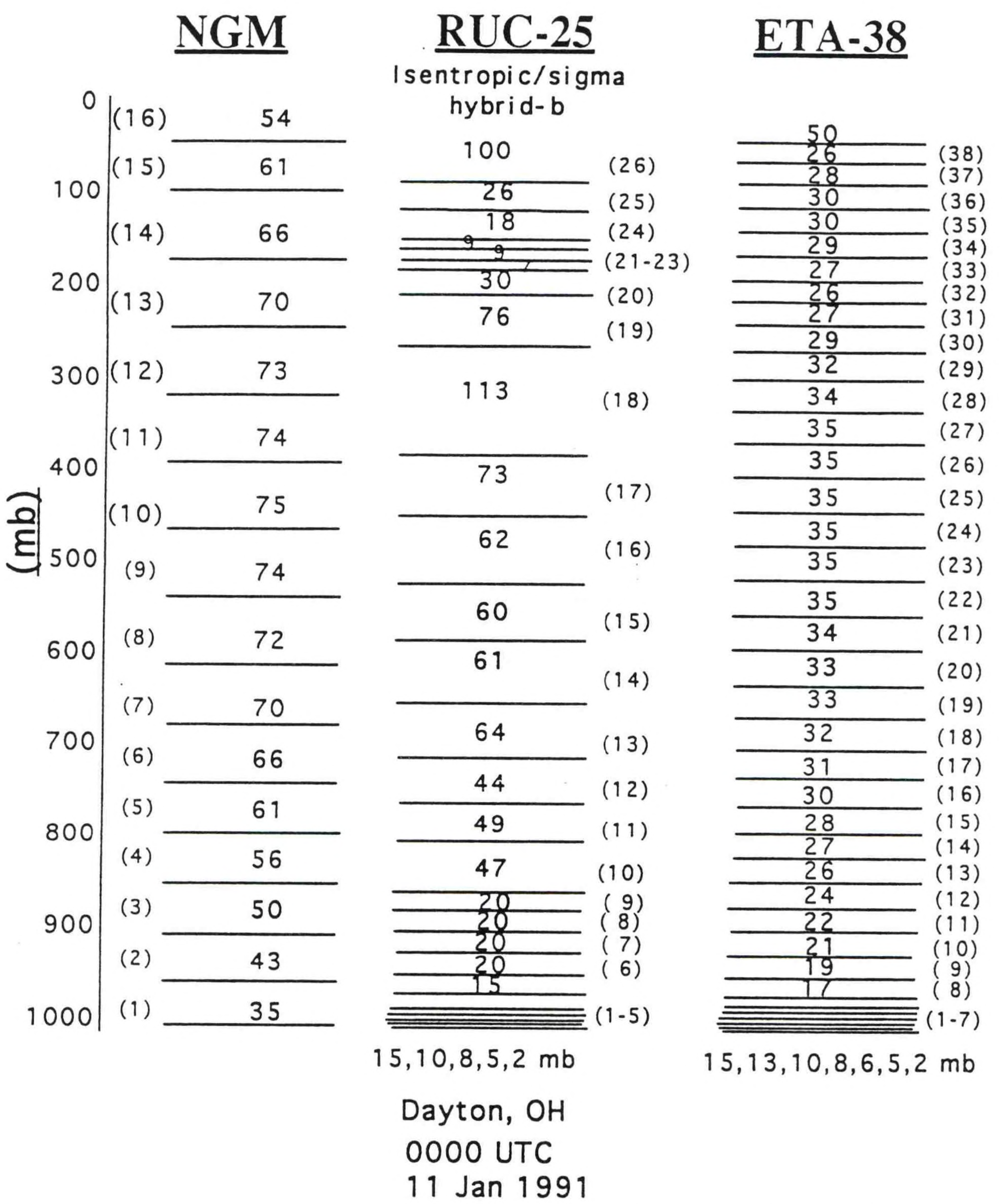

Figure 3. A comparison of vertical levels between the Nested Grid Model (NGM), the Rapid Update Cycle (RUC), and the 38 level Eta model. Layer numbers are in parentheses. Numbers between layers represent their thickness in mb.

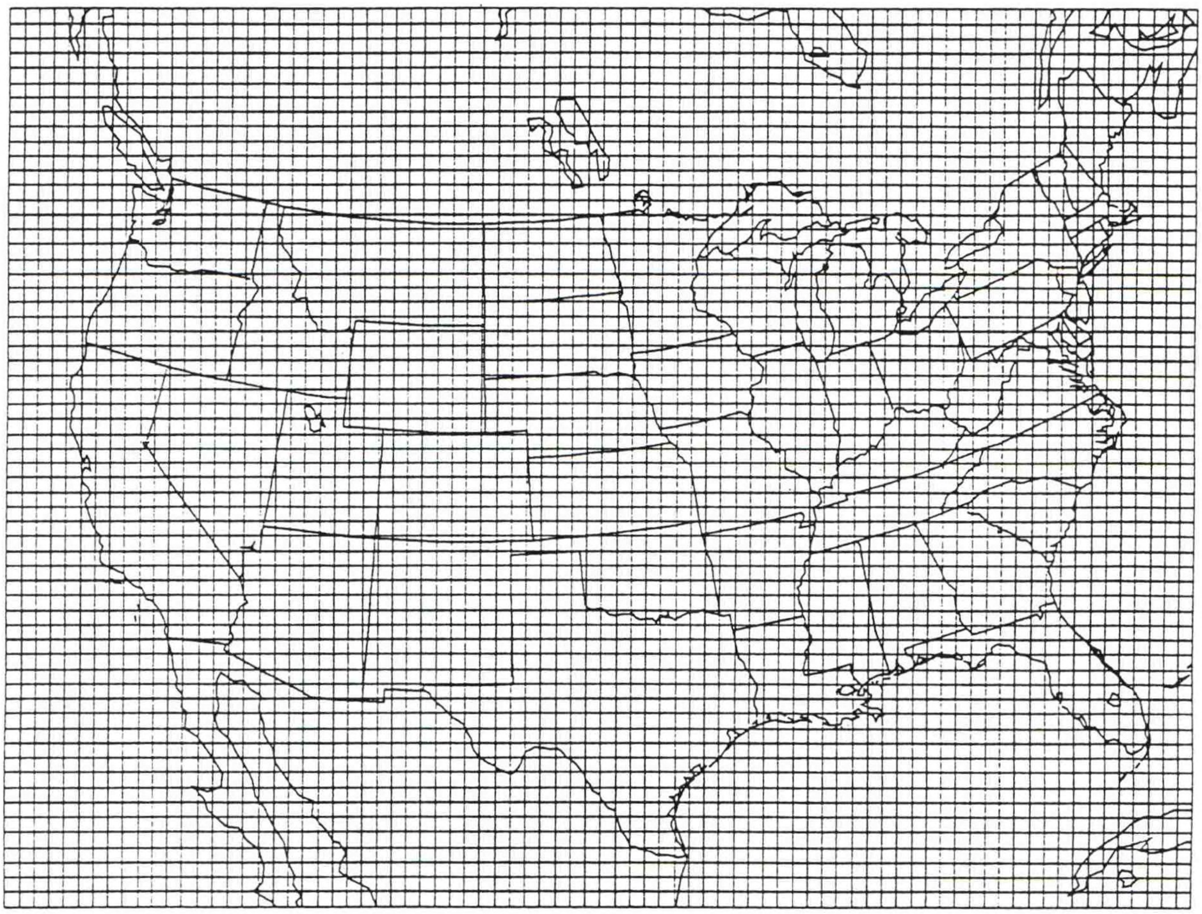

Figure 4. The current 60-km RUC horizontal grid with 5022 (81 x 62) grid points.

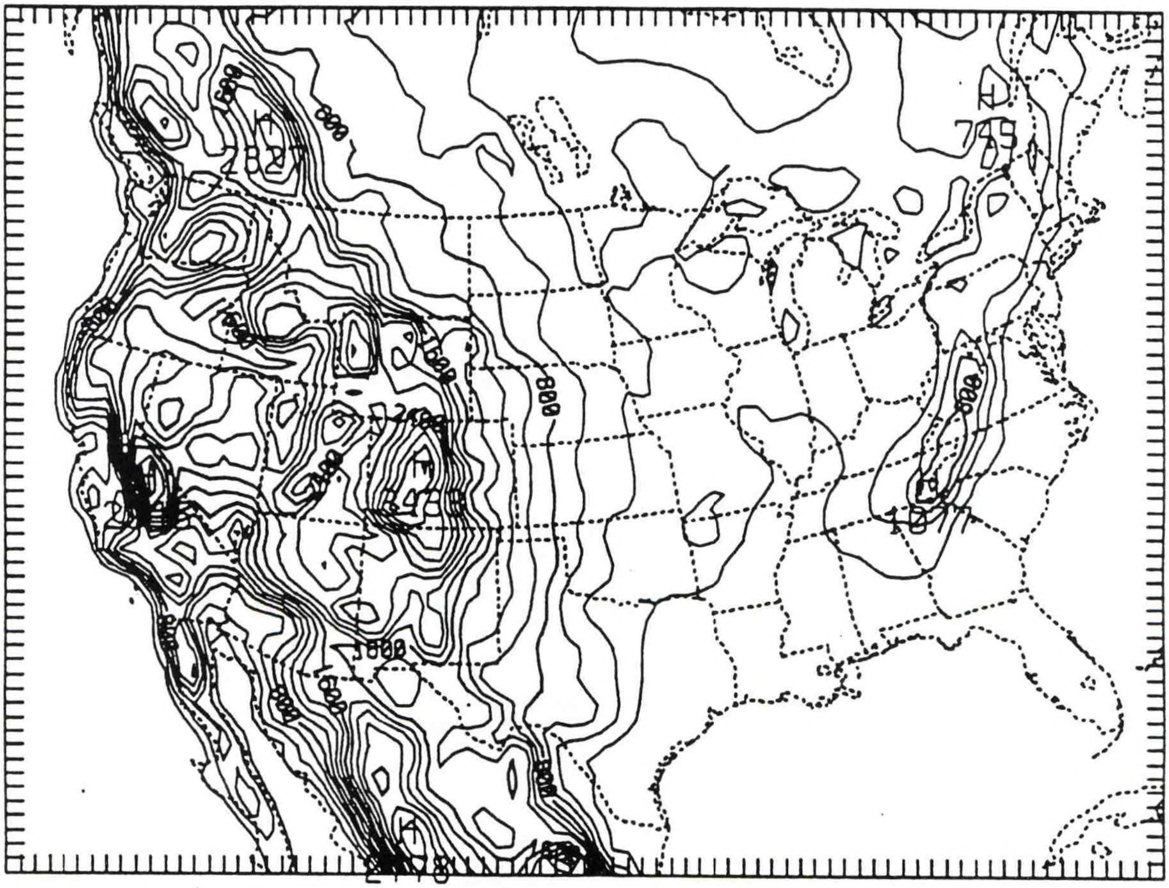

Figure 5. Elevation field used with the Rapid Update Cycle. Contour interval is 200 meters.

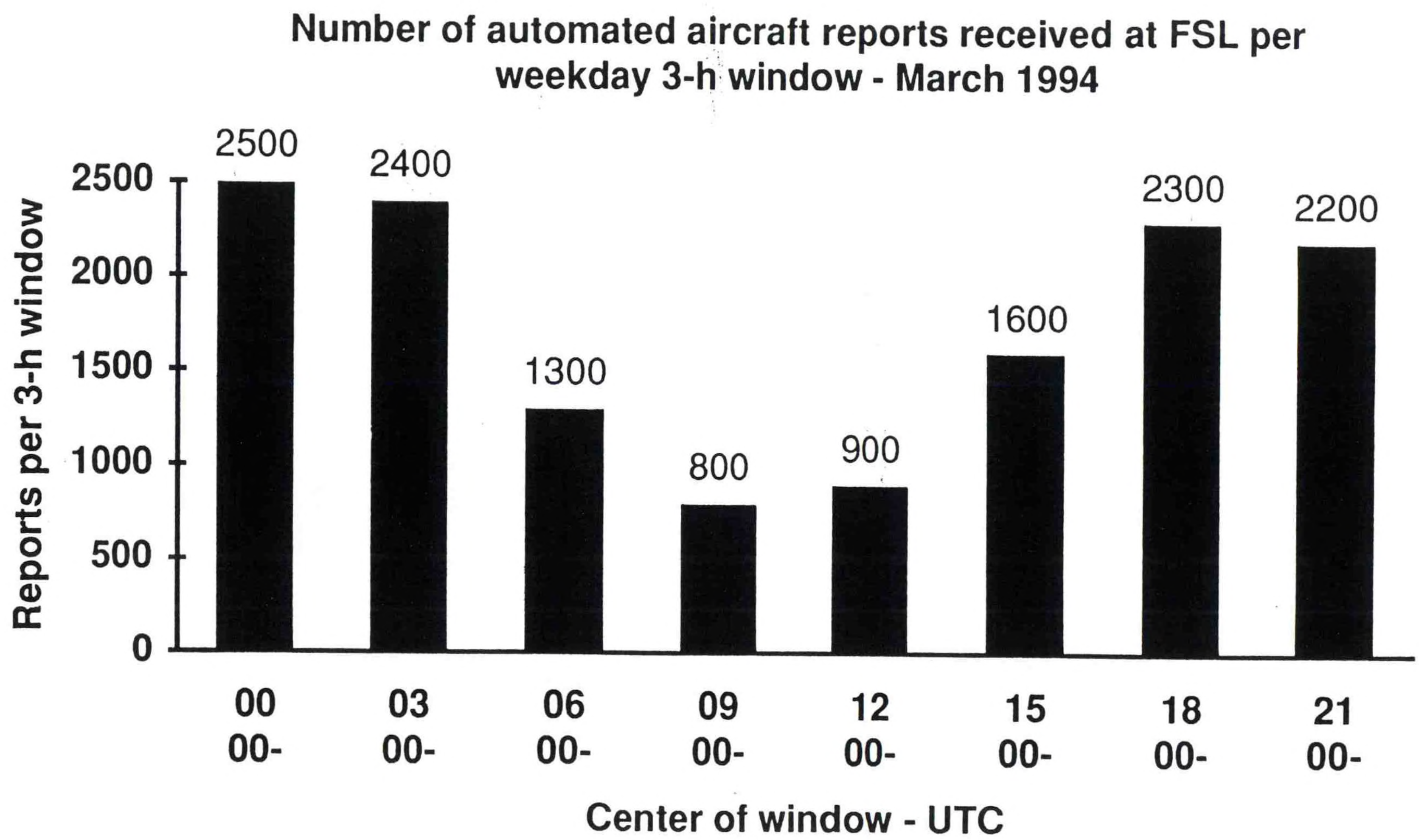

Figure 6. Volume of automated aircraft data at different times of the day averaged for March 1994 weekdays.