NWS Technical Procedures Bulletin 448

RUC-2 - The Rapid Update Cycle Version 2

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This bulletin refers to the RUC-2 40km version implemented on 6 April 1998.

Summary of RUC-2 vs. RUC-1 differences - Abstract

1. Frequency of Assimilating Observations
In the old version of the Rapid Update Cycle (RUC-1), observations are assimilated once every three hours. In the new version (RUC-2) observations are assimilated hourly.

2. Time of Availability
In the 60km RUC-1, the data cutoff time is +1h, 20 min. For the 40km RUC-2, the data cutoff time is about +0h 20 min, meaning that RUC-2 analyses and forecasts are available almost an hour earlier than those from the RUC-1. A catch-up cycle is used to assimilate late-arriving rawinsonde data at 0000 and 1200 UTC, and forecasts are run from the catch-up cycle rather than the first cycle at these times.

3. Computational Grid
RUC-2 covers a geographical domain about 50% larger in area than the 60km RUC-1, extending further in all directions, but especially in the southeast, north, and west, and covering considerably more oceanic area. Moving the boundaries slightly farther from the coasts has significantly improved forecasts in these areas. The old RUC-1 grid has 60-km resolution (81 x 62 grid) and 25 levels. The new grid has 40-km resolution (151 x 113) and 40 levels. The RUC-2 continues to use an isentropic-sigma hybrid vertical coordinate.

4. Data Assimilated
There are several new types of observations assimilated into RUC-2 not present in the 60km RUC. These include:

- VAD wind profiles
- GOES precipitable water estimates
- SSM/I precipitable water estimates
- GOES high-density cloud-drift winds (visible, IR, water-vapor cloud top)
- more complete use of high-resolution ascent/descent commercial aircraft reports

5. Moist Physics
Clouds must be inferred from the relative humidity field in RUC-1. In RUC-2, a comprehensive cloud physics package has been imported from the NCAR/Penn State MM5 mesoscale model. Mixing ratios of five types of hydrometeors are explicitly predicted: cloud water, rain water, snow, ice crystals, and graupel. Even the number density of ice crystals is predicted as part of the microphysical processes. Cloud fields initialize each RUC-2 model run, using the most recent 1-h hydrometeor forecast to avoid cloud/precipitation spin-up problems.

6. Surface Processes
The RUC-1 calculates surface fluxes using a simple surface slab with constant soil moisture availability. The RUC-2 features a multi-level soil and vegetation model with evolving soil moisture and temperature fields that are much more accurate than climatology. Snow accumulation and melting are accounted for. The 60-km RUC employs a coarse land use data and derives sea surface temperatures from climatology and does not consider snow cover. The RUC-2 employs improved land use data, including vegetation class, monthly vegetation fraction from NESDIS, and soil type; it utilizes daily detailed fields of sea-surface and lake-surface (for the Great Lakes) temperature. It also cycles snow cover and canopy water along with the soil fields to further improve short-range forecasts.

7. Turbulence
The RUC-1 computes turbulent fluxes from a formulation due to Mellor and Yamada (Level 2.0). The RUC-2 calculates the kinetic energy associated with turbulence (TKE) explicitly from equations derived by Burk and Thompson (Level 3.0). Boundary fluxes are improved using the explicit turbulence parameterization, and explicit TKE maxima are commonly found in upper-level frontal zones.

8. Radiation
There was no explicit calculation of atmospheric radiative fluxes in the RUC-1, a simplification partly responsible for its warm bias. Full atmospheric radiation imported from the MM5 model is included in RUC-2. The radiative heating/cooling is influenced by hydrometeors (clouds) at each model level.

9. Lateral boundary conditions
The old RUC-1 used lateral boundary conditions specified from the NGM model at 6-h intervals. RUC-2 uses Eta model boundary values specified at 3-h intervals.

Most significant improvements in RUC-2 fields over those from RUC-1.

- **all surface fields - temperature, moisture, winds** - From improved surface, turbulence, radiation, and cloud physics
- **precipitation - both winter and summer** - From use of MM5 microphysics and improved convective scheme with downdrafts
- **upper-level winds and temperatures** - From higher vertical and horizontal resolution, better physics
- **biases in temperature and relative humidity aloft** - From use of better radiation, cloud, and surface physics.
- **orographically induced precipitation and circulations** - From higher horizontal resolution, cloud physics, and better use of surface data near mountains.

1. INTRODUCTION AND HISTORY

A number of significant weather forecasting problems exist in the 1-12 hour range, including severe weather in all seasons (tornadoes, severe thunderstorms, winter storms) and hazards to aviation (turbulence, icing, low ceiling and visibility). Accurate 1-12 hour short-term forecasts are also important for public forecasts, for agriculture and the recreation and power-generation industries. The Rapid Update Cycle (RUC) was designed to provide accurate numerical forecast guidance for weather-sensitive users for the next 12-hour period. The RUC runs at the highest frequency of any forecast model at the National Centers for Environmental Prediction (NCEP), assimilating recent observations aloft and at the surface to provide very high frequency updates of current conditions and short-range forecasts using a mesoscale model.

This bulletin describes a new version of the RUC, called RUC-2, implemented at NCEP in April 1998. The RUC-2 produces new 3-d analyses and short-range forecasts every hour, compared to the 3-h updating in RUC-1. The original Rapid Update Cycle (RUC-1, TPB – Benjamin et al. 1994a,1994b) was implemented in September 1994 at NCEP. Some number of smaller changes were made to RUC-1 over the 1995-1996 period, but the RUC-2 is a significant advance over RUC-1, not just in assimilation frequency, but also in resolution, types of data assimilated, and model physics. These changes (summarized in the abstract at the top of this document) allow the RUC-2 to more accurately represent significant weather systems across the United States in all seasons.

The uses of the RUC are summarized below:

- **Explicit use of short-range forecasts** - The RUC forecasts are unique in that they are initialized with very recent data. Thus, in most cases, the most recent RUC forecast has been initialized with more recent data than the other forecast model runs available. Even at 0000 and 1200 UTC, when other model runs are available, the RUC forecasts are useful for comparison over the next 12 h. Although there are a vast number of differences between the RUC and other NCEP models, the key unique aspects of the RUC are its hybrid isentropic vertical coordinate (used in analysis and model), hourly data assimilation, and model physics.
- **Monitoring current conditions with hourly analyses** - Hourly analyses are particularly useful when overlaid with hourly satellite and radar images, or hourly observations such as from surface stations or profilers.
- **Evaluating trends of longer-range models** - RUC analyses and forecasts are useful for evaluation of the short-term predictions of the Eta and AVN models.

The users of the RUC include:

- Aviation Weather Center/NCEP, Kansas City, MO
- Storm Prediction Center/NCEP, Norman, OK
- NWS Weather Forecast Offices
- FAA/DOT, including use for air traffic management and other automated tools, and for FAA workstations
- NASA Space Flight Centers
- Private sector weather forecast providers

2. DOMAIN, RESOLUTION, TERRAIN FOR RUC-2

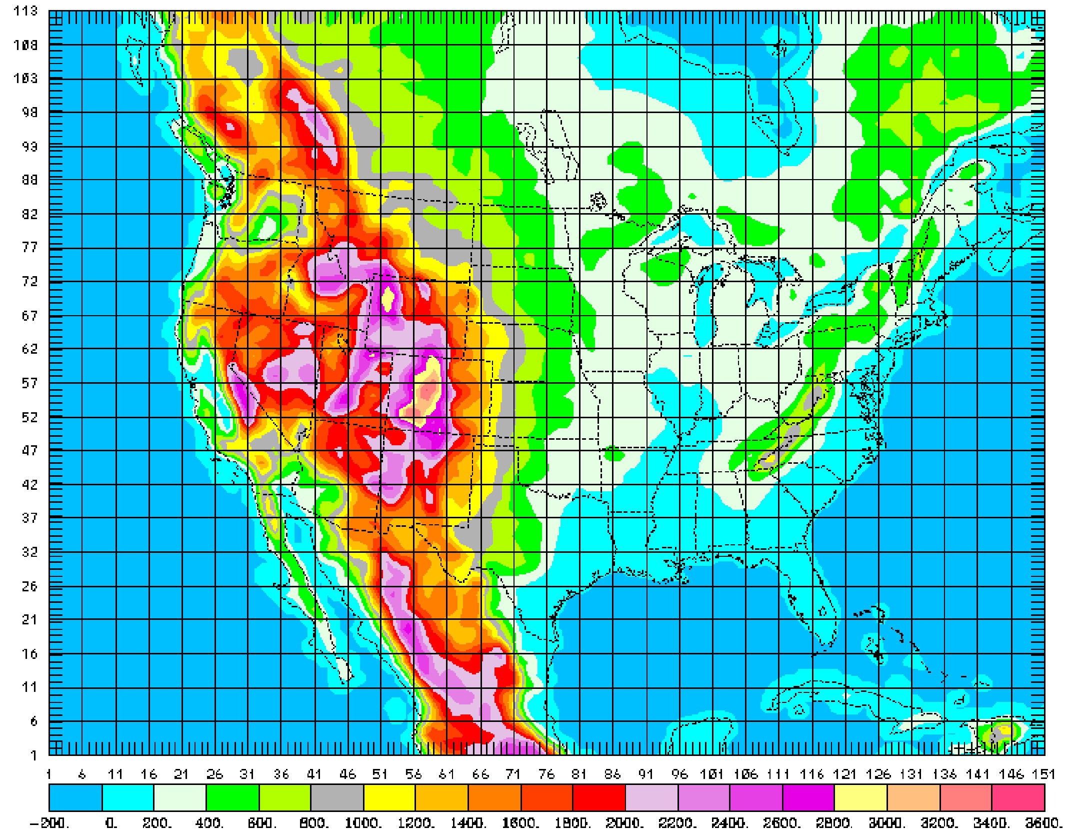

Figure 1. RUC-2 (40-km) domain and terrain elevation (m)

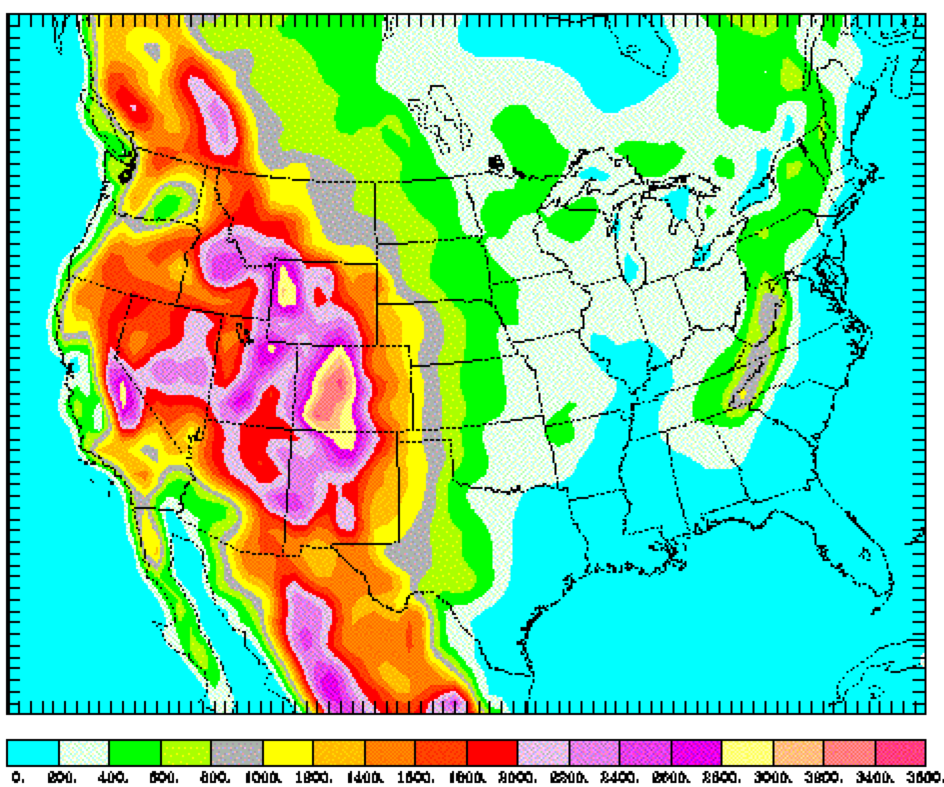

Figure 2 - RUC-1 (60-km) domain and terrain elevation (m)

2.a. Domain

The RUC-2 domain (Fig. 1) is on a Lambert conformal projection matching that used for the AWIPS 212 NWS distribution grid. The mesh is rectangular on this projection, and its size is 151x113 grid points (compared to 81x62 for RUC-1 - Fig. 2)

The grid length is 40.635 km at 35 deg N. Due to the varying map-scale factor from the projection, the actual grid length in RUC-2 varies from about 40.6 km at 35 deg N to 33 km at the north boundary. The grid length is about 38 km at 43 deg N.

The RUC-2 domain was designed to:

- provide higher horizontal resolution than RUC-1
- move the lateral boundaries slightly farther off the east and west coasts than in RUC-1 to improve coastal forecasts (a weakness of RUC-1)
- match the AWIPS 212 distribution grid to avoid interpolation and give field users the highest resolution possible.

The 40-km RUC-2 domain covers about 50% more area than the 60-km RUC-1 domain. It extends farther than the RUC-1 domain in all directions, but especially in the southeast. It covers considerably more oceanic areas than the RUC-1 domain. The RUC-2 latitude/longitude at each point in an ASCII file can be downloaded from http://ruc.fsl.noaa.gov/MAPS.domain.html. The lower left corner point is (1,1), and the upper right corner point is (151,113), as shown in the table below.

RUC-2 point	AWIPS-212 point	Latitude	Longitude
(1,1)	**(23,7)**	**16.2810 N**	**126.1378 W**
(1,113)	**(23,119)**	**54.1731 N**	**139.8563 W**
(151,1)	**(173,7)**	**17.3400 N**	**69.0371 W**
(151,113)	**(173,119)**	**55.4818 N**	**57.3794 W**

2.b. Horizontal resolution

Horizontal resolution in RUC-2 is 40 km compared to 60 km for the RUC-1. The higher resolution allows considerable improvement in resolution of topography and also in detail of land-water boundaries. This improves the ability of the RUC-2 to resolve local circulations and orographic precipitation patterns. Because the RUC-2 model has less internal smoothing than the Eta or NCAR/Penn State MM5 models, these features tend to be fairly well depicted considering its 40-km resolution.

2.c. Vertical resolution

The RUC-2 has 40 vertical levels compared to 25 levels in RUC-1. The RUC-2 continues to use a generalized vertical coordinate configured as a hybrid isentropic-sigma coordinate in both the analysis and model. This coordinate has proven to be very advantageous in RUC-1 in providing sharper resolution near fronts and the tropopause (e.g., Benjamin 1989, Johnson et al. 1993, Zapotocny et al. 1994). Some of the other advantages include:

- All of the adiabatic component of the vertical motion on the isentropic surfaces is captured in flow along the 2-d surfaces. Vertical advection, which usually has somewhat more truncation error than horizontal advection, does much less "work" in isentropic/sigma hybrid models than in quasi-horizontal coordinate models. This characteristic results in improved moisture transport and less precipitation spin-up problem in the first few hours of the forecast.
- Improved conservation of potential vorticity. The potential vorticity and tropopause level (based on the 2.0 PV unit surface) show very good spatial and temporal coherence in RUC-2 grids.
- Observation influence in the RUC-2 analysis extends along isentropic surfaces, leading to improved air-mass integrity and frontal structure.

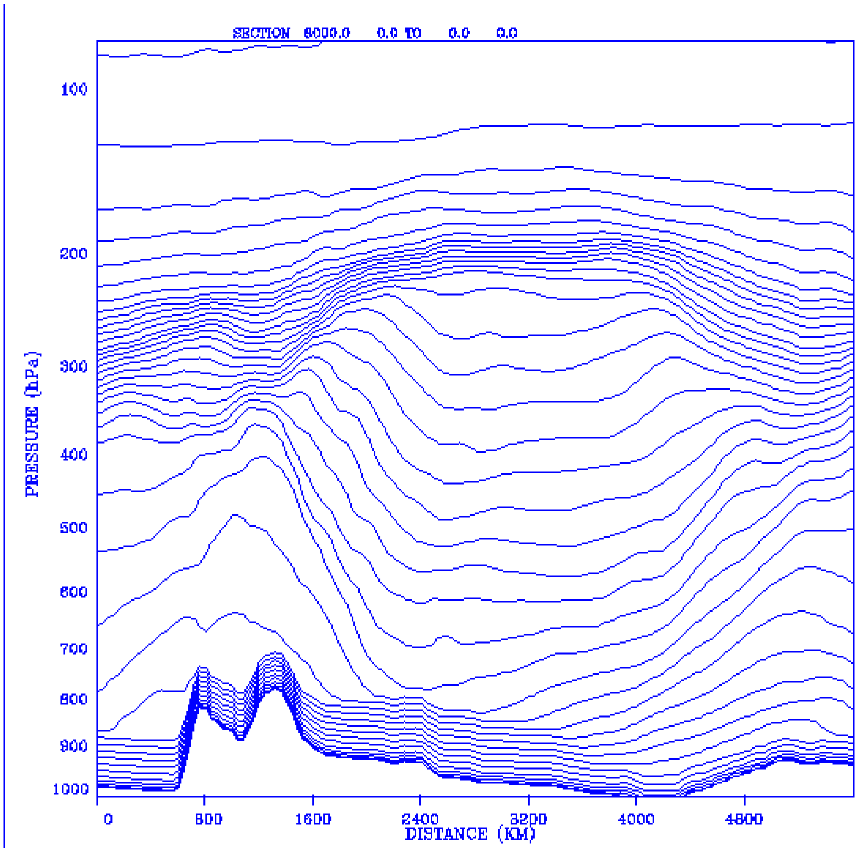

Figure 3. Vertical cross-section of RUC-2 native levels, depicting hybrid isentropic-sigma vertical coordinate.

A sample cross section of RUC-2 native levels is displayed in Fig. 3. The cross-section is oriented from west on the left to east across southern Canada, passing north of Vancouver, and though James Bay near the 4000-km distance mark. The central part of the cross-section has relatively warm air, with lowered isentropes, but cold air on the east side, with only a few levels near the surface indicated as terrain-following. The cross section is for a RUC analysis valid at 1800 UTC 24 February 2000.

The typical RUC-2 resolution near fronts and the tropopause is apparent in this figure, as well as the tendency for more terrain-following levels to "pile up" in warmer regions (the western and central part of the cross section, in this case). The hybrid isentropic-sigma coordinate is defined by a 20-line section of code in both the analysis and forecast model. The rest of the code treats the analysis/model processes as a generalized vertical coordinate. The 20-line section of code can be changed to define a pure sigma terrain-following coordinate and has been tested in this mode. In the RUC-2 (as well as in RUC-1), analysis/model levels that are isentropic in part of the domain can become terrain-following in other parts, as shown in Fig. 3. A reference potential temperature is assigned to each of the 40 levels (Table 1).

Table 1. RUC-2 reference potential temperatures

224.	232.	240.	245.	250.	255.	260.	265.
270.	274.	278.	282.	286.	290.	294.	297.
300.	302.	304.	306.	308.	310.	312.	314.
316.	318.	320.	322.	325.	328.	331.	334.
337.	341.	347.	355.	364.	375.	400.	450.

The pre-specified pressure spacing in RUC-2, starting from the ground is 2, 5, 8, and 10 mb, followed by as many 15-mb layers as are needed. (Near-surface pressure spacing between levels in RUC-1 was 20 mb.) This terrain-following spacing becomes compacted as the terrain elevation increases, as shown over the Canadian Rockies in Fig. 3. Very high resolution of the boundary layer is provided in all locations, including over higher terrain. The lowest atmospheric level in RUC-2 is set at 5 m above the model terrain height. The effects of this choice are discussed in the analysis and model sections, but since the RUC-2 has an explicit level actually *at* the surface, no extrapolation from higher levels is necessary to diagnose values at the surface. The minimum potential temperature spacing occurs through much of the troposphere and is 2 K instead of 4 K as in RUC-1. The top level in RUC-2 is at 450 K as opposed to 410 K in RUC-1. Overall, the vertical resolution is somewhat higher both in the boundary layer and free atmosphere, and the domain extends farther into the stratosphere.

2.d. Terrain
The most obvious difference, of course, between terrain in RUC-2 (Fig. 1) and that in RUC-1 (Fig. 2) is that finer-scale topographical features are distinct in the RUC-2 terrain. RUC-2 analyses and forecasts can depict many significant topographically induced features, including mountain/valley circulations, mountain waves, sea breezes, and orographic precipitation patterns. The surface elevation of the RUC-2 is defined as a "slope envelope" topography instead of the previous full envelope topography used in RUC-1. The envelope topography is defined by adding the sub-grid-scale terrain standard deviation (calculated from a 10-km terrain field) to the mean value over the grid box. In the slope envelope topography, the terrain standard deviation is calculated with respect to a plane fit to the high-resolution topography within each grid box. This gives more accurate terrain values, especially in sloping areas at the edge of high-terrain regions. It also avoids a tendency of the standard envelope topography to project the edge of plateaus too far laterally onto low terrain regions. Using the slope envelope topography gives lower terrain elevation at locations such as Denver and Salt Lake City which are located close to mountain ranges.

3. ANALYSIS METHOD FOR RUC-2

3.a. Data assimilated
The new data sets assimilated in the 40-km RUC-2 include:

- VAD wind profiles
- high-resolution ascent-descent aircraft reports
- ship reports
- GOES integrated precipitable water retrievals
- SSM/I integrated precipitable water retrievals
- GOES high-density cloud drift winds
- tropical storm dropwindsonde data - reconnaissance

Satellite-based precipitable water retrievals and cloud-drift winds are currently used only over water points. Satellite observations over land will be ingested in the near future. Wind profiler, rawinsonde, aircraft, and surface (land and buoy) observations continue to be utilized in the RUC-2, as they were for RUC-1, except that the wind profiler and rawinsonde data are used with higher vertical resolution due to the 40 levels in RUC-2. Here is a summary of the actual measurements used from other data sets:

- Rawinsonde/dropwindsonde - temperature, height, moisture, wind
- Aircraft - wind, temperature
- Surface - wind, temperature, dewpoint, altimeter setting

More information on the use of wind data in RUC-2 is available in Smith and Benjamin (1998).

3.b. Optimum interpolation analysis
The optimal interpolation multivariate analysis used in RUC-1 has been substantially modified for the RUC-2, providing, among other things, closer fit to observations, better use of aircraft ascent/descent winds and temperatures, and greater efficiency. A discussion of optimal interpolation analysis in isentropic coordinates is provided in Benjamin (1989).

Sequence in RUC-2 analysis

- Read in observations
- Subject observations to gross quality control checks (range limits, wind shear, lapse rate)

- Read in background (previous 1-h forecast, if available). RUC-2 will "cold start" with an Eta forecast background if the RUC has not been running within last 12 hours.
  This background field is defined at the (x,y,p) points of the hybrid coordinate surfaces for the background field. The quality control and analysis steps below are carried out at these (x,y,p) points. This will result in changes to virtual potential temperature at these points. For the RUC-2, the next-to-last step (bullet) is in effect a repositioning of the coordinate surfaces to correspond to the results of the analysis steps that precede it.
- Perform precipitable water analysis and modify background moisture values according to precipitable water observations (currently -- GOES and SSM/I, future - GPS). In this precipitable water "pre-analysis", the shape of the water vapor mixing ratio in the background grid field is left intact, but is either moistened or dried out according to the observations. (Benjamin et al. 1998b)
- Perform buddy-check quality control. Flag suspicious observations. (See quality control section below.)
- Calculate super-observations. This procedure combines observations that are near to each other in space. It prevents against the possibility of ill-conditioned matrices in the optimum interpolation analysis.
- Multivariate z/u/v analysis at all levels. A level-dependent partial geostrophic constraint is applied, weakest at the surface and in the boundary layer. The wind analysis is anisotropic and oriented along the flow, according to the geostrophically derived horizontal covariances of forecast error (Benjamin 1989).
- Height analysis increment (z') calculated in last step is vertically differentiated to obtain a temperature increment. This temperature increment is added to the temperature field. Now the temperature (virtual potential temperature) background is an updated field that has taken into account the height observations and wind observations through the partial geostrophic constraint.
- Calculate surface pressure increment from multivariate z' increment at surface. This provides an updated background field for the univariate surface pressure analysis a few steps down. The height analysis is essentially ignored from this step on, since a hydrostatic integration will occur at the end of the analysis to calculate heights.
- Perform univariate temperature (theta-v) analysis at all levels using temperature observations. Now the direct temperature observations (e.g., surface, aircraft, rawinsonde, RASS) have also been incorporated.
- Perform univariate wind analysis at lowest 5 levels. This analysis uses the result of the previous multivariate analysis as its background. This step forces close matching to surface wind observations. No geostrophic constraint is applied at this step.
- Perform univariate analysis for pressure at surface. This step forces close fitting to surface pressure observations (calculated through the altimeter setting).
- Perform univariate moisture (condensation pressure) analysis at all levels. The moisture variable stored in RUC-2 is water vapor mixing ratio, but inside the RUC-2 analysis, values are converted to condensation pressure, since this variable varies with fewer orders of magnitude over the depth of the troposphere than water vapor mixing ratio.
- All calculations up to this point have been done to change values at the (x,y,p) points of the background field. The exact same procedure could have been applied to a background from a sigma or eta coordinate model. In the case of the RUC-2, these values are adjusted (vertically interpolated) to the hybrid isentropic-sigma coordinates.
- Hydrostatic integration to recalculate z (height) at all levels. Thus, the RUC-2 mass field changes are all made through the virtual potential temperature field at all levels and the surface pressure field. The height observations influence these fields, as described above.
- Diagnose other variables from analysis - e.g., special levels such as freezing level, maximum wind level, tropopause level, etc.

The RUC-2 analysis provides de facto analyses of cloud variables and soil variables by using the previous 1-h forecast of these variables as initial conditions for the next run. Although use of observations will later provide improved fields for these variables (e.g., Kim and Nychka 1998), this "cycling" provides substantial improvement over zero initial clouds and climatology for soil variables.

3.c. Incorporation of the surface analysis within the 3-d analysis

With the 1-h assimilation cycle, the RUC-2 integrates into one system the RUC-1 and RSAS (RUC Surface Analysis System) from the 60-km era. The RUC-2 surface analyses are improved over those from RUC-1 due to the use of a forecast background combined with new design features to ensure that the 40km surface analyses not only draw more closely to the data, but also have better consistency and reliability. Specific advantages of RUC-2 surface analyses over those from RUC-1 are:

- use of a forecast background rather than persistence
- multivariate/univariate two-pass analysis for winds/pressure instead of a single-pass univariate analysis
- consistency in data-void regions with terrain-induced dynamics and surface physics in the 40-km version, allowing features of the background (forecast) fields such as mountain/valley circulations, drainage winds, effects of variations in soil moisture, vegetation type, land use, roughness length, snow cover, land/water contrast, and explicit clouds to be present in the analysis.
- improved quality control due to the forecast background. This is a fairly significant item, as the 60km QC led to frequent bulls-eyes that could only be eliminated by black-listing problematic stations
- lack of spurious temperature, moisture, and wind gradients at ocean or data-void boundaries.

The following new features are added to ensure that the 40km RUC-2 analyses draw very closely to surface data:

- All station pressure (altimeter) and surface wind observations are used regardless of the difference between station and model elevation. The pressure is reduced to the model elevation using the local lapse rate over the bottom 5 levels in the background field.
- Temperature and dewpoint observations are reduced, via the local lapse rate, from model terrain height to actual station elevation, provided, however, that the reduction does not exceed 70 mb. With this change and the higher-resolution 40km terrain, a far higher percentage (95%) of surface temperature and dewpoint observations in the western U.S. are used in the 40km 3-d analysis than in the 60km RUC-1 3-d analysis.
- The surface wind analysis is performed in two passes, as noted earlier. The first pass is a multivariate wind/height analysis with weak geostrophic coupling since some correlation between the actual and geostrophic winds is expected at the surface, especially over water. The second pass uses the first pass as its background and is univariate, so that local details, particularly in the wind observations, are drawn for.
- Expected surface observation errors for the 40km RUC-2 (a parameter in the analysis) have been reduced from values in the 60km RUC to force closer fit to observations.
- Through use of a minimum topography field, surface temperature and dewpoint are diagnosed at close to the station elevation in both the RUC-1 and RUC-2. The minimum topography field is determined from a high-resolution 10km topography field, with the value for the grid box being the *minimum* 10km elevation, which is representative of valley elevations in rough terrain. The rationale is that surface stations in mountainous areas are usually located in valleys or open parks at lower elevation.
- The reduction from the model topography to the minimum topography is done using the model lapse rate limited to be between the dry adiabatic and isothermal.

3.d. Quality control

As in RUC-1, quality control in RUC-2 involves a buddy check. The buddy check is of observation residuals, the differences between the observation and the background field interpolated to the observation point, and not of the observations alone. This is an important distinction, since it means that any known anomaly in the previous forecast has already been subtracted out, improving the sensitivity of the QC procedure to actual errors. At each observation point, the parameter in question is estimated via optimum interpolation of values from surrounding observation points. If the estimated and measured values differ by more than a prescribed amount, further checks determine whether the central observation or one of its neighbors is erroneous.

Bird contamination for radar/profiler winds

Checks are made for bird contamination for both VAD and profiler winds in RUC-2. A careful check for bird (and other) contamination in profiler winds is made at the Profiler Hub in Boulder, CO. This check includes use of second-moment data to examine for likelihood of bird contamination. If the quality control flag produced by this check indicates suspicious data, the profiler data at that level is not used by RUC-2. For VAD winds, no second-moment data is available, so a cruder and more conservative check is made. A solar angle is calculated, and if the sun is down and the temperature is warmer than -2 deg C, VAD winds are not used if they have a northerly component between 15 August and 15 November or a southerly component between 15 February and 15 June.

4. ONE-HOUR ASSIMILATION CYCLE FOR RUC-2

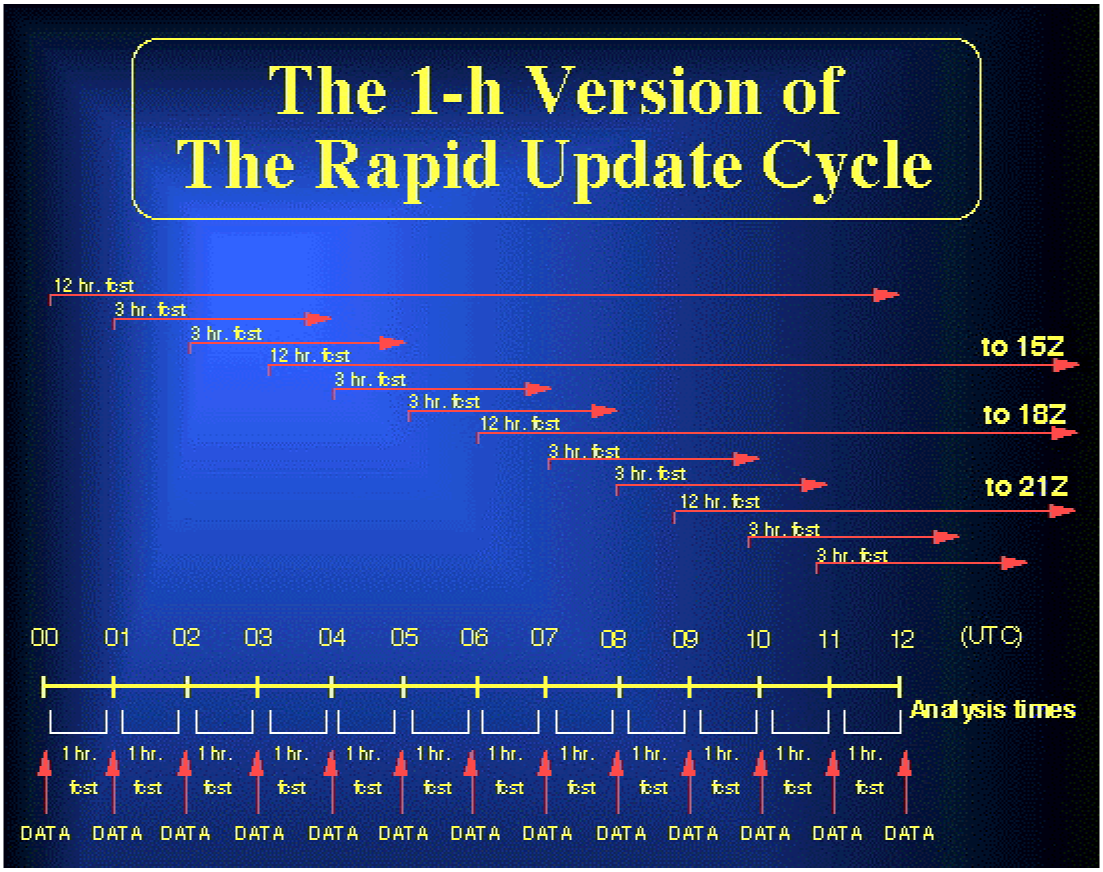

Figure 4. Schematic of RUC 1-h assimilation cycle.

The background for each analysis in the 1-h assimilation cycle is the previous 1-h forecast, as shown in Fig. 4. The 1-h cycle allows much more complete use of profiler, surface, and VAD data, which are all available at least hourly. The time window for aircraft data is now -1h to 0h instead of -2h to +1h, meaning that aircraft data are now applied closer to the time that they are actually reported.

The data availability is considerably improved with the implementation of the RUC-2. Grids from RUC-2 are available almost 1 hour earlier than those from RUC-1. The data cut-off time from the 40km system is 20 min after the analysis valid time. A catch-up cycle at 0000 and 1200 UTC runs at +55 min to catch late-arriving rawinsonde data. Twelve-hour forecasts from these times are run from the catch-up cycle analysis, rather than the "early look" analysis at 20 min after each hour.

5. RUC-2 FORECAST MODEL

The RUC-2 forecast model is an updated version of 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 isentropic-sigma coordinate described in section 2.c to either a pure sigma or pure isentropic model.
The RUC-2 model is considerably different from the RUC-1 model in its parameterizations of physical processes such as cloud microphysics (stable precipitation), turbulent mixing, radiation, and convective precipitation. To some extent, this was made possible by changing the RUC-2 model to use the code structure of the NCAR/Penn State Mesoscale Model version 5 (MM5, Grell et al. 1994). This allowed relatively easy transfer of MM5

parameterizations (cloud microphysics, radiation) into the RUC-2 model, and will continue to do so in the future as new MM5 parameterizations are developed.

5.a. Basic dynamics/numerics Here are some of the basic numerical characteristics of the RUC-2 model:

- Arakawa-C staggered horizontal grid (Arakawa and Lamb 1977); u and v horizontal wind points offset from mass points to improve numerical accuracy.
- No vertical staggering.
- Time step is 60 seconds at 40-km resolution.
- Positive definite advection schemes used for continuity equation (advection of pressure thickness between levels) and for horizontal advection (Smolarkiewicz 1983) of virtual potential temperature and all vapor and hydrometeor moisture variables.

The atmospheric prognostic variables of the RUC-2 forecast model are:

- pressure thickness between levels
- virtual potential temperature
- horizontal wind components
- water vapor mixing ratio
- cloud water mixing ratio
- rain water mixing ratio
- ice mixing ratio
- snow mixing ratio
- graupel (rimed snow) mixing ratio
- number concentration for ice particles
- turbulence kinetic energy
- turbulent variance of potential temperature
- turbulent variance of water vapor mixing ratio
- turbulent covariance of potential temperature perturbations with water vapor mixing ratio perturbations

The soil prognostic variables (at six levels) of the RUC-2 forecast model are:

- soil temperature
- soil volumetric moisture content

Other surface-related prognostic variables are snow water equivalent moisture and snow temperature.

5.b. Physical parameterizations

Explicit cloud/moisture processes. The explicit microphysics from the NCAR/Penn State mesoscale model MM5 (level 4, Reisner et al. 1998) is used, with five hydrometeor species -- cloud water, rain water, snow, ice, graupel (mixing ratios for each) and also with an explicit prediction of ice particle number concentration. This improvement was made to provide improved forecasts of clouds, icing, and precipitation from RUC-2. In the 60km RUC-1, stable precipitation was defined simply by supersaturation removal, with no treatment of cloud or ice processes. All of the cloud variables are cycled in the 40-km RUC-2, meaning that there are initial cloud fields for each run. In the RUC-2 model, all six cloud variables are advected using the positive definite scheme of Smolarkiewicz (1983) on the isentropic-sigma levels with adaptive vertical resolution. The incorporation of this scheme into RUC-2 is described in detail by Brown et al. (1998).

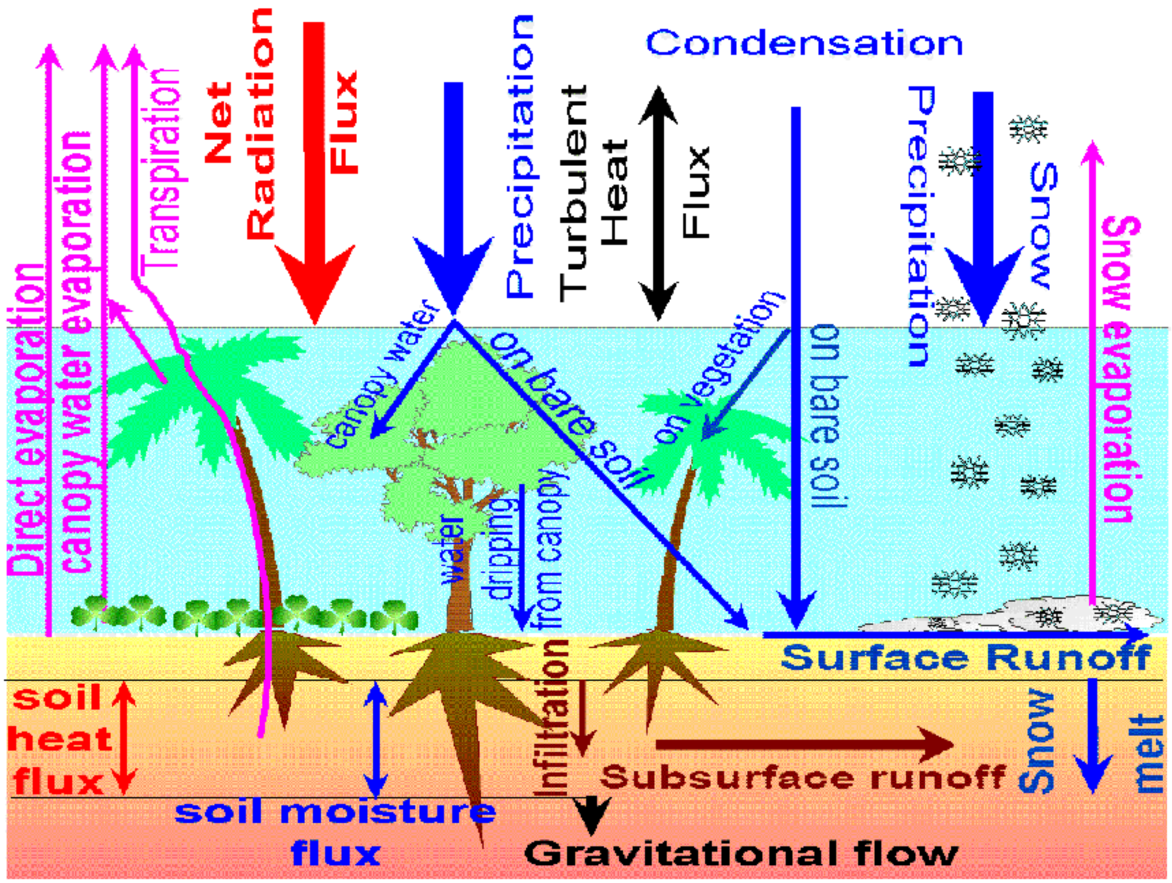

Figure 5. Schematic of processes treated in RUC-2 land-surface model component in forecast model.

Improved surface physics. The RUC-2 includes a 6-layer soil/vegetation/snow model (Fig. 5) to improve forecasts of low-level conditions. Surface (shelter/anemometer level) forecasts are often critically dependent on accurate estimates of surface fluxes, and in turn, on reasonably accurate soil moisture and temperature estimates. The RUC-2 soil model contains heat and moisture transfer equations solved at 6 levels at each grid point together with the energy and moisture budget equations for the ground surface (Smirnova et al. 1997a,b). The heat and moisture budgets are applied to a thin layer spanning the ground surface and including both the soil and the atmosphere with corresponding heat capacities and densities. A treatment of the evapotranspiration process, developed by Pan and Mahrt (1987), is implemented in the MAPS/RUC soil/vegetation scheme. In the presence of snow cover, snow is considered to be an additional upper layer of soil that interacts with the atmosphere, significantly affecting its characteristics (Smirnova et al 1998).

The snow model contains a heat-transfer equation within the snow layer together with the energy and moisture budget equations on the surface of the snow pack. This budget is applied to the entire snow layer if the snow depth is less than a threshold value, currently set equal to 7.5 cm, or to the top 7.5 cm layer of snow if the snow pack is thicker. Snow evaporates at a potential rate unless the snow layer would all evaporate before the end of the time step. In this case the evaporation rate is reduced to that which would just evaporate all the existing snow during the current time step. A heat budget is also calculated at the boundary between the snow pack and the soil, allowing melting from the bottom of the snow layer. Melting at the top or bottom of the snow layer occurs if energy budgets produce temperatures higher than the freezing temperature (0 deg C). In this case the snow temperature is set equal to the freezing point, and the residual from the energy budget is spent on melting snow. Water from melting snow infiltrates into the soil, and if the infiltration rate exceeds the maximum possible value for the given soil type, then the excess water becomes surface runoff.

The accumulation of snow on the ground surface is provided by the microphysics algorithm of the MAPS/RUC forecast scheme (Reisner et al. 1998, Brown et al. 1998). It predicts the total amount of precipitation and also the distribution of precipitation between the solid and liquid phase. The subgrid-scale ("convective") parameterization scheme also contributes to the liquid precipitation. With or without snow cover, the liquid phase is infiltrated into the soil at a rate not exceeding maximum infiltration rate, and the excess goes into surface runoff. The solid phase in the form of snow or graupel is accumulated on the ground/snow surface and is unavailable for the soil until melting begins. The RUC-2 surface package provides surface temperature and dewpoint forecasts that are clearly superior to those of the RUC-1 due to improved surface heat and moisture fluxes. The soil temperature and moisture has been evolving since 29 April 1996, leading to fairly accurate estimates of these fields, certainly much better than climatology (Smirnova et al. 1997b).

Atmospheric radiation. The MM5 atmospheric radiation package (Dudhia 1989, Grell et al. 1994) is used in the RUC-2, with additions for attenuation and scattering by all hydrometeor types. This scheme is a broadband scheme with separate components for longwave and shortwave radiation. In the RUC-1, there was no atmospheric radiation at all, only a surface radiation budget with clouds diagnosed from relative humidity. The solar flux at the top of the atmosphere is now variable, taking into account the elliptical orbit of the earth around the sun.

Turbulent mixing. In RUC-2, turbulent mixing at all levels, including the boundary layer, is prescribed the explicit turbulence scheme of Burk and Thompson (1989). This scheme is a level-3.0 scheme, with explicit forecast of turbulent kinetic energy and three other turbulence variables, replacing the Mellor-Yamada level-2.0 scheme in RUC-1. The surface layer mixing continues to be prescribed by Monin-Obukhov similarity theory, specifically the three-layer scheme described in Pan et al. (1994). With the Burk-Thompson scheme, the RUC-2 typically forecasts TKE amounts of 5-20 J/kg in the boundary layer, and also forecasts TKE maxima aloft, typically localized in frontal zones, corresponding to likely areas for clear-air turbulence.

Convective parameterization. A version of the Grell (1993) convective parameterization is used, updated from that used in the RUC-1, including fixes to downdraft detrainment, calculation of cloud top, minimum cloud depth, and capping criteria. This version gives somewhat larger amounts of precipitation and more coherent patterns in convective areas than the RUC-1 version. The inclusion of downdrafts in the Grell scheme results in smaller-scale details in RUC-2 warm season precipitation patterns than may be evident in that from the Eta model, which currently uses the Betts-Miller-Janjic convective parameterization. This same difference in character of precipitation forecasts is also evident in NCEP/NSSL experiments comparing the Kain-Fritsch (which also includes downdrafts) and Betts-Miller-Janjic schemes both within the MesoEta model (Kain et al. 1998).

5.c. Lateral boundary conditions Lateral boundary conditions for the RUC-2 model are provided by the early Eta run output at 3-h intervals. The Eta model forecasts are interpolated to the 40-km RUC-2 domain on its hybrid coordinate levels. Values of pressure thickness, virtual potential temperature, and horizontal winds at the edge of the RUC-2 domain (up to 5 grid points from the boundary) are nudged (Davies 1976) toward the Eta values at each time step in a model run.

The accuracy of RUC-2 forecasts is driven to some extent by the time availability of Eta forecasts. RUC-2 forecasts initialized at 0000 or 1200 UTC are forced to use boundary conditions from Eta runs already 12 h old, since the RUC-2 runs before the Eta. This means that the 12-h RUC-2 forecasts valid at 0000 or 1200 UTC are nudging toward 24-h Eta forecasts at these times. Typically, the skill of RUC-2 forecasts jumps near the western boundary by the 0300 or 1500 UTC runs, respectively, since the newer Eta runs are available by those times.

5.d. Fields for surface boundary conditions

- Daily 50-km resolution sea-surface temperatures- NCEP. The same SST field used for the Eta model is also used for the RUC-2, including 14-km resolution lake-surface temperatures for the Great Lakes.
- Daily ice cover - NESDIS/NCEP - same as used for Eta
- Monthly vegetation fraction data at a resolution of 0.14 degrees latitude - NESDIS/NCEP - same as used for Eta
- Seasonal (4 seasons) albedo at 1 deg resolution.
- Land use (14 classes) at 1 deg resolution.
- Soil texture at 1 deg resolution

The snow fields cycled by RUC-2 seem to be more accurate than the daily U.S. Air Force snow cover analysis. Improved surface fields (land use, soil texture) will added as they become available for the RUC-2 domain.

6. RUC-2 OUTPUT VARIABLES AND FILES

6.a. Basic 3-d output variables

In RUC-2, water vapor mixing ratio replaces condensation pressure (output in RUC-1) as the water vapor moisture variable in the 3-d grids. Height also replaces Montgomery stream function. The use of height and water-vapor mixing ratio instead of the variables they replace facilitates calculation of derived quantities involving these variables. Height also stores more efficiently in GRIB.

6.b. RUC 2-d diagnosed variables

A variety of 2-d fields are diagnosed as part of the RUC post-processing, including surface fields, precipitation type, freezing level, maximum wind level, tropopause level, and 30-mb layer mean fields. The following diagnosed fields were added to the RUC-2 output in January 1990:

- PBL height
- gust wind speed
- cloud base height
- cloud top height
- visibility
- pressure of maximum equivalent potential temperature in column
- convective cloud top height
- equilibrium level height

The method for diagnosing some of the output fields in RUC post-processing is described below:

Relative humidity - Defined with respect to saturation over water in the RUC isobaric fields and in the surface relative humidity field.

Freezing levels - Two sets of freezing levels are output from RUC-2, one searching from the bottom up, and one searching from the top down. Of course, these two sets may be equivalent under most situations, but they may sometimes identify multiple freezing levels. The bottom-up algorithm will return the surface as the freezing level if any of the bottom three native RUC-2 levels (up to about 50 m above the surface) are below freezing (per instructions from Aviation Weather Center, which uses this product). The top-down freezing level returns the first level at which the temperature goes above freezing searching from the top downward. For both the top-down and bottom-up algorithms, the freezing level is actually interpolated between native levels to estimate the level at which the temperature goes above or below freezing.

Tropopause Pressure - Diagnosed from the 2.0 isentropic potential vorticity unit (PVU) surface. The 2.0 PVU surface is calculated directly from the native isentropic/sigma RUC grids. First, a 3-d PV field is calculated in the layers between RUC levels from the native grid. Then, the PV=2 surface is calculated by interpolating in the layer where PV is first found to be less than 2.0 searching from the top down in each grid column. Low tropopause regions correspond to upper-level waves and give a quasi-3D way to look at upper-level potential vorticity. They also correspond very well to dry (warm) areas in water vapor satellite images, since stratospheric air is very dry.

MAPS mean sea-level pressure - This reduction is the one used in previous version of RUC using the 700 mb temperature to minimize unrepresentative local variations caused by local surface temperature variations. This reduction is described in Benjamin and Miller (1990, October, Monthly Weather Review, pp. 2099-2116.) This method has some improvement over the standard reduction method in mountainous areas and gives geostrophic winds that are more consistent with observed surface winds.

3-h surface pressure change - These fields are determined by differencing surface pressure fields at valid times separated by 3 h. Since altimeter setting values (surface pressure) are used in the RUC analyses, this field reflects the observed 3-h pressure change fairly closely over areas with surface observations. It is based on the forecast in data-void regions.
-The 3-h pressure change field during the first 3 h of a model forecast often shows some non-physical features, resulting from gravity wave sloshing in the model. After 3 h, the pressure change field appears to be quite well-behaved. The smaller-scale features in this field appear to be very useful for seeing predicted movement of lows, surges, etc. despite the slosh at the beginning of the forecast.

2m temperature, dewpoint temperature - Temperature and dewpoint temperatures displayed are extrapolated to a "minimum" topography field to give values more representative of valley stations in mountainous areas, where surface stations are usually located.

Precipitation accumulation - All precipitation values, including the 12-h total, are liquid equivalents, regardless of whether the precipitation is rain, snow, or frozen.

Resolvable and sub-grid scale precipitation - In RUC-2 (and RUC-1), the forecast model uses the Grell (1993) convective parameterization scheme. This scheme tends to force grid-scale saturation in its feedback to temperature and moisture fields. One result of this is that the precipitation from weather systems that might be considered to be largely convective will be reflected in the RUC-2 model with the Grell scheme with a substantial proportion of resolvable-scale precipitation. Thus, the sub-grid scale precipitation from RUC2 should not be considered equivalent to "convective precipitation".

Snow accumulation - Snow accumulations are calculated using a 10 to 1 ratio between snow depth and liquid water equivalent. Of course, this ratio varies in reality, but the ratio used here was set at this constant value so that users will know the water equivalent exactly. The snow accumulation (through the snow liquid water equivalent) is not diagnosed based on temperature, but is explicitly forecast through the mixed-phase cloud microphysics in the MAPS model.

Snow depth - This field is the current estimated snow depth (using a 2.5 to 1 ratio between snow and liquid water equivalent). It evolves in the RUC-2 1-h cycle, increasing from accumulation from the explicit snowfall in the RUC-2 from the cloud microphysics, and decreasing from melting depending on an energy budget in the snow layer in the RUC-2 model. This field has been evolving since the beginning of the snow season in fall 1997. As of early January 1998, the maximum depth in the RUC-2 domain was 2 meters over the mountains of British Columbia, equivalent to 0.8 meters of liquid water using the 2.5 - 1 ratio.

Categorical precipitation types - rain/snow/ice pellets/freezing rain - These yes/no indicators are calculated from the explicit cloud microphysics in the RUC-2 model (from NCAR/Penn State MM5 model**).** <u>These values are not mutually exclusive. More than one value can be yes (1) at a grid point.</u> Here is how the diagnostics are done:

Diagnostic logic for precipitation types

- Snow -

  There are a few ways to get snow.
  - If fall rate for snow mixing ratio at ground is at least 0.2 x 10^{-9} g/g/second, snow is diagnosed.
  - If fall rate for graupel mixing ratio at ground is > 1.0 x 10^{-9} g/g/s and
    - surface temp is < 0 deg C, and max rain mixing ratio at any level < 0.05 g/kg or the graupel rate at the surface is less than the snow fall rate, snow is diagnosed.
    - surface temp is between 0 - +2 deg C
- Rain - If the fall rate for rain mixing ratio at ground is at least 0.01 g/g/second, and the temperature at the surface is > or = 0 deg C, then rain is diagnosed. The temperature used for this diagnosis is that at the minimum topography, described above.
- Freezing rain - Same as for rain, but if the temperature at the surface is < 0 deg C **and** some level above the surface is above freezing, freezing rain is diagnosed.
- Ice pellets - If
  - the graupel fall rate at the surface is at least 1.0 x 10^{-9} g/g/s and
  - the surface temp is < 0 deg C and the max rain mixing ratio in the column is > 0.05 g/kg and

- the graupel fall rate at the surface is greater than that for snow mixing ratio,

  then ice pellets are diagnosed.

CAPE - Convective available potential energy - indicates energy available for buoyant parcel from native RUC-2 hybrid-b level with maximum buoyancy within 180 mb of surface (changed to 300 mb on 6 May 1999). Before the most buoyant level is determined, first an averaging of potential temperature and water vapor mixing ratio is done in the lowest seven RUC native levels (about 40 mb).

CIN - Convective inhibition - indicates negative buoyancy in layer through which a potentially buoyant parcel must be lifted before becoming positively buoyant.

Lifted index / Best lifted index - Lifted index uses the surface parcel, and best lifted index uses buoyant parcel from the native RUC-2 level with maximum buoyancy within 180 mb of surface (changed to 300 mb on 6 May 1999).

Precipitable water - Integrated precipitable water vapor from surface of RUC model to top level (~50 mb). The RUC-2 run at NCEP includes assimilation of GOES and SSM/I precipitable water observations. The precipitable water calculation is performed by summing the product of the specific humidity at each level times the mass of each surrounding layer. This mass layer is bounded by the mid-points between each level, since the native RUC vertical grid is non-staggered.

Helicity - Helicity is calculated using the same technique as used for the Eta. The following discussion is modified from a discussion of the Eta helicity product on the NCEP/EMC FAQ web page: The 0-3km storm-relative helicity grids uses the technique described in Davies-Jones et al. (1990). The mean-layer wind in the cloud bearing layer is estimated with the 850-300mb layer-average wind. For wind speed less than 15 m/s the storm motion vector is estimated as 75% of the magnitude and 30 degrees to the right of the 850-300mb mean-layer wind. For wind speeds greater than 15 m/s the storm motion vector is estimated as 80% of the magnitude and 20 degrees to the right of the 850-300mb mean-layer wind. The storm-relative helicity is then integrated for the 0-3km AGL layer of the model atmosphere using wind data for each RUC-2 model layer.

The Davies-Jones paper states that values in the 150-900 range can correspond with tornadic thunderstorms. Helicity is basically a measure of the low-level shear, so in high shear situations, such as behind strong cold fronts or ahead of warm fronts, the values will be very large maybe as high as 1500. High negative values are also possible in reverse shear situations.

Soil moisture - cycled continuously since 26 April 1996. There are 6 levels in the 40-km RUC soil model, extending down to 3 m deep, but the field shown is for the top 2 cm of soil only, so this field responds quickly to recent precipitation or surface drying and may not be indicative of deep soil moisture. The variable displayed is the soil volumetric moisture content, the ratio of water volume to total volume in the soil. Values of 0.25 or so are relatively high values.

6.c. 40km RUC file output formats

From the 40km RUC at NCEP, four different output files will be available:

- isobaric main (25-mb) grids of primary six 3-d variables plus about 77 2-d fields (including precipitation, fluxes, CAPE/CIN, tropopause fields, surface fields, fields from special levels - mean layers near surface, freezing level, max wind, etc.)
  (~6 MB in GRIB format per output time)
- native (hybrid coordinate) grids of 3-d variables plus 2-d fields
  (~10 MB in GRIB format per output time)
- surface grids (25 2-d fields)
  (0.35 MB per output time)
- model output (BUFR) soundings at several hundred sites (standard sounding variables plus surface variables).

```
Naming convention for those four output files:

isobaric main:
   RUC/ruc2.yymmdd/ruc2.TXXZ.pgrbanl
     or
   RUC/ruc2.yymmdd/ruc2.TXXZ.pgrbfzz

native:
   RUC/ruc2.yymmdd/ruc2.TXXZ.bgrbanl
     or
   RUC/ruc2.yymmdd/ruc2.TXXZ.bgrbfzz
     XX = cycle time (01,02,03..)
   - zz = forecast hour (00,01,02...)

surface:
   RUC/ruc2.yymmdd/ruc2.TXXZ.sgrbanl
     or
   RUC/ruc2.yymmdd/ruc2.TXXZ.sgrbfzz

BUFR sounding:
   RUC/ruc2.yymmdd/ruc2.TXXZ.bufranl
     or
   RUC/ruc2.yymmdd/ruc2.TXXZ.bufrfzz
```

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