Cloud/Hydrometeor Assimilation into 20-km Rapid Update Cycle

Dongsoo Kim* and Stanley G. Benjamin

NOAA Research – Forecast Systems Laboratory
**Also affiliated with CIRES/University of Colorado*
Boulder, CO 80305 USA

1. Introduction

Toward the goal of improved short-range forecasts of cloud/hydrometeors, icing, and precipitation, an advanced version of the Rapid Update Cycle (RUC) cloud-top pressure assimilation technique has been developed and tested. This improved technique, using GOES single field-of-view sounder derived cloud-top pressure data provided by NESDIS, is being implemented into operations at the National Centers for Environmental Prediction (NCEP) along with a major upgrade to the RUC in April 2002. This new version, called RUC20 (*Benjamin et.al* 2003), also includes a change in horizontal resolution from 40 km to 20 km and significant changes to the analysis and model forecast components.

Previous versions of the RUC technique for assimilation of GOES cloud-top pressure are discussed by *Kim and Benjamin* (2001, 2000). In this paper, we present more recent modifications to the RUC cloud/hydrometeor analysis technique using GOES cloud-top data as well as initial experiments toward assimilation of radar reflectivity.RUC mixed-phase cloud microphysics and cycling of cloud/hydrometeor fields

2. RUC mixed-phase cloud microphysics and cycling of cloud/hydrometeor fields

The 20-km RUC uses a bulk mixed-phase cloud microphysics scheme from the NCAR/Penn State MM5 model, with 5 hydrometeor types explicitly forecast (*Brown et al*. 2000). The prognostic variables in this scheme are mixing ratios of water vapor, cloud water, rain water, ice, snow, and graupel, and number concentration of ice particles. Each of these variables is explicitly forecast at each 3-D grid point in the RUC model. This approach is different (and more complicated) than diagnostic mixed-phase schemes in which total condensate is the only prognostic variable, such as the schemes used in the NCEP Eta model.

An improved version of the RUC/MM5 mixed-phase cloud microphysics scheme is being implemented with the rest of the RUC20 at NCEP. This improved version provides more realistic forecasts of supercooled liquid water and reduces unrealistically large amounts of graupel.

Previously in the 40-km RUC-2 (RUC40), the initial conditions for the fields were simply those carried over from the previous 1-h RUC forecast. In the RUC20, including assimilation of GOES cloud-top data, these fields are modified each hour as part of the cloud clearing and cloud building. Cloud-top pressure shows where clouds are and are not present, but does not show cloud depth. Further, unless there are broken layers, they cannot provide information on multiple cloud layers. Thus, the RUC cloud/hydrometeor assimilation technique is designed to use this partial information. When GOES data indicate that no clouds are present, the technique removes any hydrometeors and reduces water vapor mixing ratio to a subsaturation value, namely, relative humidity not to exceed 80%. When GOES data indicates the presence of clouds, but not at the correct level in the RUC 1-h forecast, cloud water and/or ice is added in a layer of not more than 50 hPa depth. This layer is also saturated with respect to water or ice with a linear variation between these two saturation vapor pressure values in the 248-263 K range. The RUC 1-h forecast of cloud-top level is determined when any of hydrometeors in the column exceed the threshold value of 10^{-7} Kg/Kg.

3. Recent modifications for assimilation of GOES cloud-top pressure data

The RUC20 cloud/hydrometeor technique is an advanced version of the techniques previously described by *Kim and Benjamin* (2001, 2000). Recent changes to the RUC cloud/hydrometeor analysis technique include the following:

- Re-derivation of cloud-top pressure from GOES cloud-top temperature if the original retrieval of cloud-top pressure is greater than 620 hPa. This re-derivation of the cloud-top pressure uses the RUC 1-h temperature/moisture profile at the nearest grid point.
- Use of single field-of-view GOES data (~10-km resolution) instead of the previous 3x3 retrievals (~40-km resolution). The median values from the fields-of-view around each RUC box are used. Cloud fraction is calculated with this sampling into RUC grid volumes.
- Use of stability check to identify possible sub-field-of-view variations from small convective clouds that result in inaccurate cloud-top temperature and pressure determination.
- Remove cloud indicators if they only occur at isolated (non-contiguous) RUC grid points, again on the presumption that GOES may be observing sub-field-of-view clouds.
- Special handling for marine stratus situations to force cloud-top at consistent level with top of marine inversion in RUC background profile.

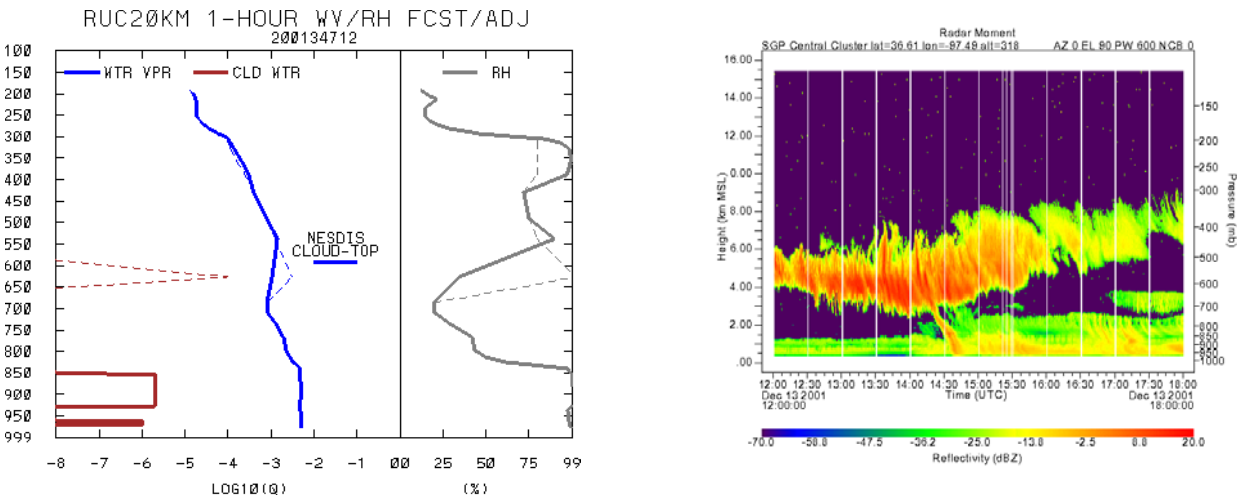

Fig.1 An example of adjustment of water vapor and cloud water mixing ratio given NESDIS' cloud-top pressure(left) and corresponding adjustment of relative humidity on the right. The mixing ratio profiles of water vapor and cloud water are valid 1200 UTC 13 December 2001 at ARM/CART site, Lamont Oklahoma. The profiles are compared with time-height image of millimeter wave cloud-profiling radar at nearby location.

Figure 1 is an example of a single column at the ARM/CART site at Lamont, Oklahoma. On the left, thick lines show 1-h forecast of water vapor and cloud water mixing ratio profiles. With the NESDIS cloud-top data at 591 hPa and meeting conditions to build cloud, the water vapor is increased such that the relative humidity is 100% near that level. Also, the cloud water mixing ratio is increased as half of the auto-conversion parameter (10-4 in this case, dashed lines are adjusted ones). The clouds are cleared above the cloud-top pressure level such that relative humidity is not greater than 80%.

The impact of GOES cloud-top data on the forecast is evaluated by routinely computing statistics of differences between GOES cloud-top pressure and the RUC40 and RUC20 forecasts (1, 3, 6, 9, 12 h) every 3 hours. The most useful summary verification product has been the correlation coefficient between RUC forecasts and GOES values. Figure 2a,b show the correlation coefficient between the NESDIS GOES cloud-top and forecasts from the RUC40 (without cloud-top assimilation) and RUC20 (with cloud-top assimilation). The RUC20 shows higher cloud-top forecast accuracy at all forecast projections from 1h to 12h. This forecast improvement in the RUC20 s attributed to both he GOES cloud-top assimilation as well as model improvements.

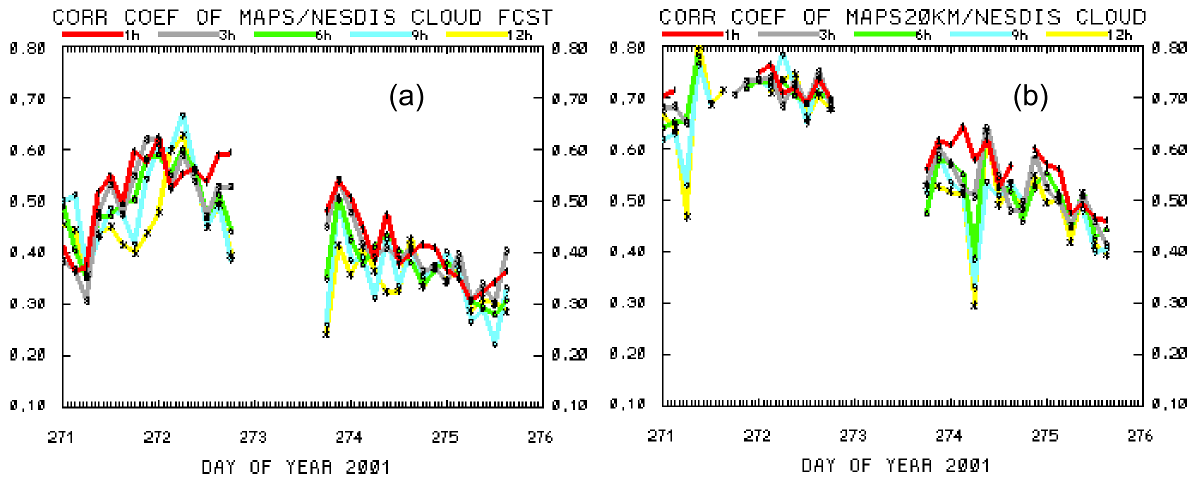

Fig. 2. Cloud-top pressure forecast verification time series for 29 Sept – 2 Oct 2001. Correlation coefficient (y-axis) between forecast and NESDIS cloud-top pressure product for forecasts from 1-12 h for a) RUC40 without cloud-top assimilation and b) RUC20 with cloud-top assimilation.

4. Assimilation of radar reflectivity data

The hourly GOES cloud-top data assimilation described in section 3 improved hydrometeor distribution, but their impact is limited on the adjusting top-boundary of hydrometeors. We extended our hydrometeor assimilation by including real-time NEXRAD reflectivity data (*Kim and Benjamin* 2001).

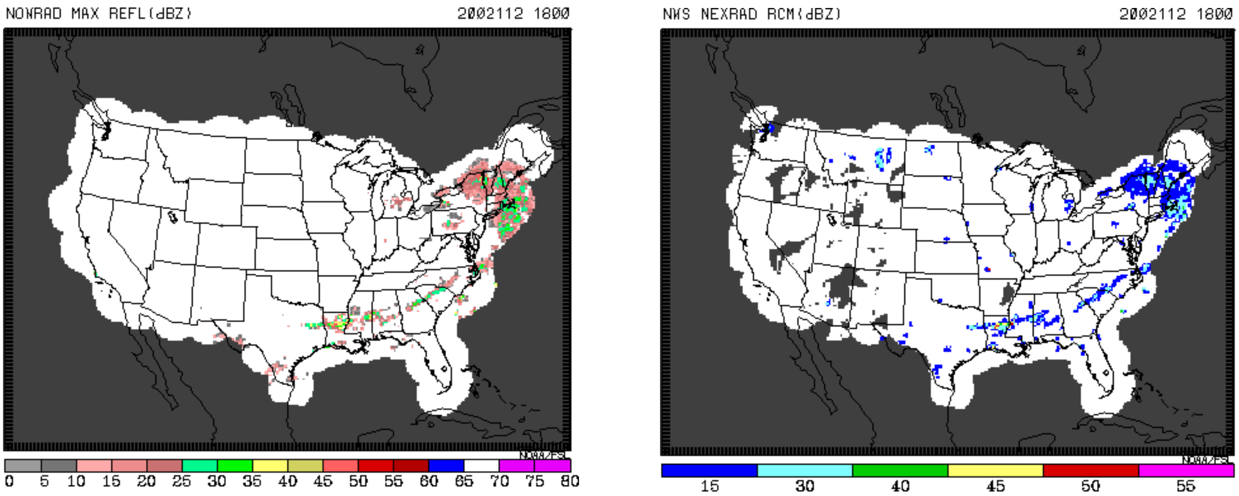

Fig.3 Reflectivity data from WSR-88D valid at 188 UTC 22 April 2002. a) Processed by WSI with manual editing, b) Provided by NWS with automatic QC. NWS' radar coded messages show beam shadow(blockage) in dark grey colour due to topography.

The RUC is testing a real-time reflectivity mosaic from the Weather Services International (WSI) and National Weather Services (NWS). WSI's reflectivity data are 2-km resolution and manually edited version of maximum reflectivity data with 15-min ingest frequency at FSL. The NWS' radar coded messages are 10-

km resolution data with automatic QC and 30-min ingest frequency. As seen in Figure 3, WSI's reflectivity has better dynamic range but there are no distinction of no-echo and no-coverage.

Within reflectivity data coverage by NWS' radar coded messages, we adjust mixing ratios of rainwater, ice, snow, and graupel such that maximum reflectivity (dBZ) of the column is close to the WSI maximum reflectivity. This process critically depends on the predicted hydrometeor distribution and the forward model. Since we do not know the level of maximum reflectivity, we use a predicted level. If WSI's maximum reflectivity is greater than 20 dBZ, then we assume that precipitation is reaching the ground. If the model fails to predict any hydrometeors, we adjust either rain or snow mixing ratios as the function of temperature in low 200 hPa above the ground. If the model predicts any hydrometeor, then the model predicted maximum reflectivity level is used to add hydrometeors down to the surface. In the case of mixed species, we calculate reflectivity for each species from the predicted profiles, and then the mixing ratios of each species are adjusted according to relative contributions among four species.

The forward model for reflectivity data is based on *Rogers and Yau* (1989):

$$Y = c \log_{10}\left[b \sum a_j Q_j \right]$$

where c is 17.8, b is 264083.11, and a_j is coefficients assigned to a species of rain water, ice, snow, and graupel (1, 0.2, 0.2, 2.0 respectively), Q_j is the mixing ratio in g/g for ith species, and Y is reflectivity (in dBZ).

Figure 4 shows an example of hydrometeor adjustment given 30 dBZ of WSI's reflectivity. The level of the maximum in computed reflectivity is 550 hPa, where the snow is only species. Therefore, snow and rain water mixing ratio profiles are adjusted. The adjustment of hydrometeor profile is applied to whole RUC domain. Figure 5a is the computed maximum reflectivity from a RUC20 3-h forecast, and Fig. 5b is the adjusted maximum reflectivity, and Fig.3a is the observed reflectivity used for the adjustment.

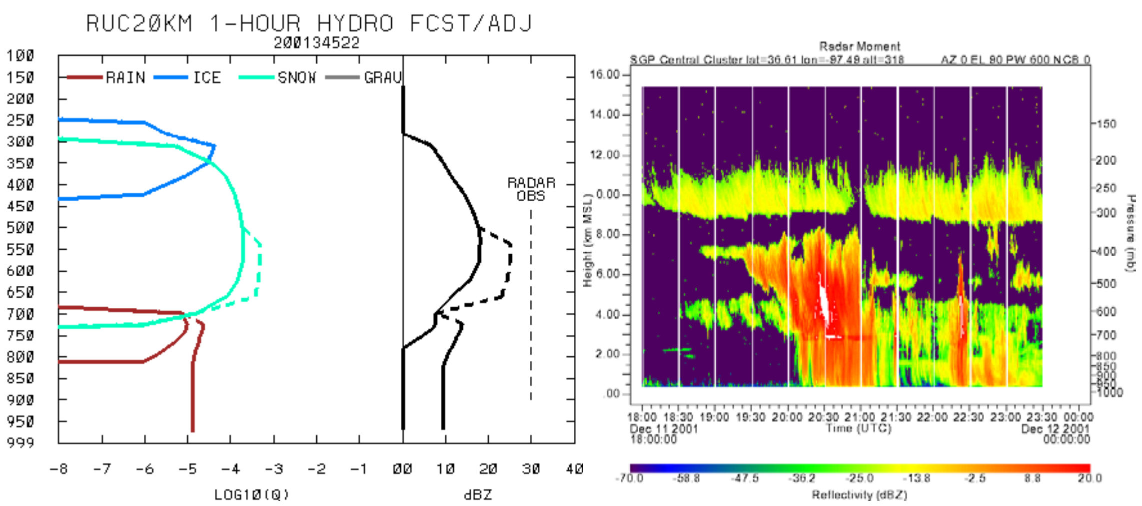

Fig.4 An example of adjustment of species of rain, ice and snow mixing ratios given WSI's reflectivity data (left) and vertical distribution of total reflectivity valid 2200 UTC 11 December 2001. This example shows that only snow and rain mixing ratios are adjusted with respect to 30 dBZ of WSI's maximum reflectivity.

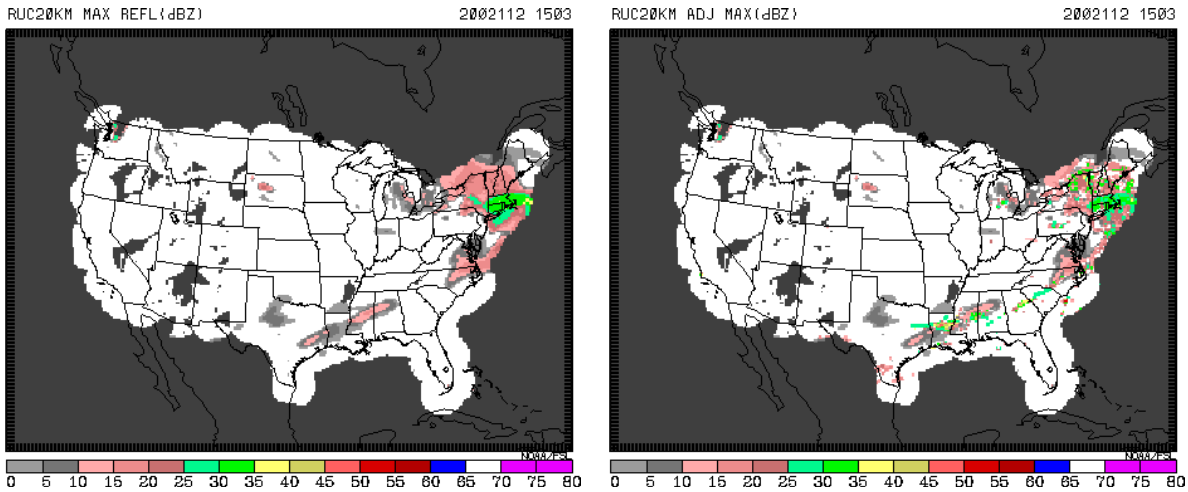

Fig.5 The computed maximum reflectivity valid at 1800 UTC 22 April 2002 a) from the RUC20 3-h forecast, and b) from the adjusted hydrometeor profiles of the RUC20 3-h forecast. The adjusted reflectivity field is closer to observed reflectivity in Fig.3.

5. Parallel experiment and precipitation verification

In April 2002, a parallel cycle of the RUC20 was started with hourly radar reflectivity assimilation. Since the cloud-top assimilation is already implemented in the operational RUC20 without radar reflectivity assimilation, it is used as the control experiment. The NCEP Stage II hourly quantitative precipitation estimation (QPE) (*Baldwin and Mitchell* 1997) is used to verify precipitation forecasts. The Stage II precipitation data are at 4-km resolution and are derived from both NEXRAD reflectivity and gauge observations. The original 4-km resolution Stage II precipitation data are remapped to the RUC20 grid by taking the maximum value in the grid box to represent the grid point. Figures 6a and b are examples of accumulated forecast precipitation from a sequence of 1-h forecasts in RUC20 assimilation cycles over an 88-h period. Figure 6a is from the control run (without radar reflectivity assimilation) and Fig. 6b is from the parallel run. These were compared with NCEP's Stage II precipitation data derived from WSR-88D reflectivity and rain gauge data over the same 88-h period (Fig. 6c). A spatial correlation field was computed as a measure of precipitation verification (*Webster and Oliver* 2001). The spatial cross-correlation is a function of x-y displacement between two fields, QPF and QPE within a predetermined evaluation window (60 x 60 grid points on a 20-km grid). Figures 6a and b are corresponding spatial cross correlation contours. The distance of maximum correlation to the center (zero displacement) is a measure of QPF phase error, and the maximum value of correlation coefficient provides an approximate measure of forecast accuracy modulated by spatial variability of rainfall amount. The shape of the contours gives information on the directional dependency of precipitation forecast accuracy.

The two contour fields were compared with the spatial auto correlation field (Fig. 6f), which is computed from the QPE against itself. The preferred orientation of reflectivity during this period is evident, with strong anisotropy oriented from WSW to NNE. The spatial patterns also depend on the duration of accumulation. As an overall assessment, better QPF should result in a QPF-QPE correlation pattern similar to that of the spatial auto correlation. In the example shown in Fig 6e, the maximum value of cross- correlation coefficient of the parallel run (with radar reflectivity assimilation) is 0.63, better than 0.46 for the control run (without radar reflectivity assimilation), indicating that the QPF error in the parallel run is reduced from that of the control run. Also, the contour lines of the parallel run result are better defined, suggesting that its spatial scales and directional orientations are more accurate than those of the control run in this case.

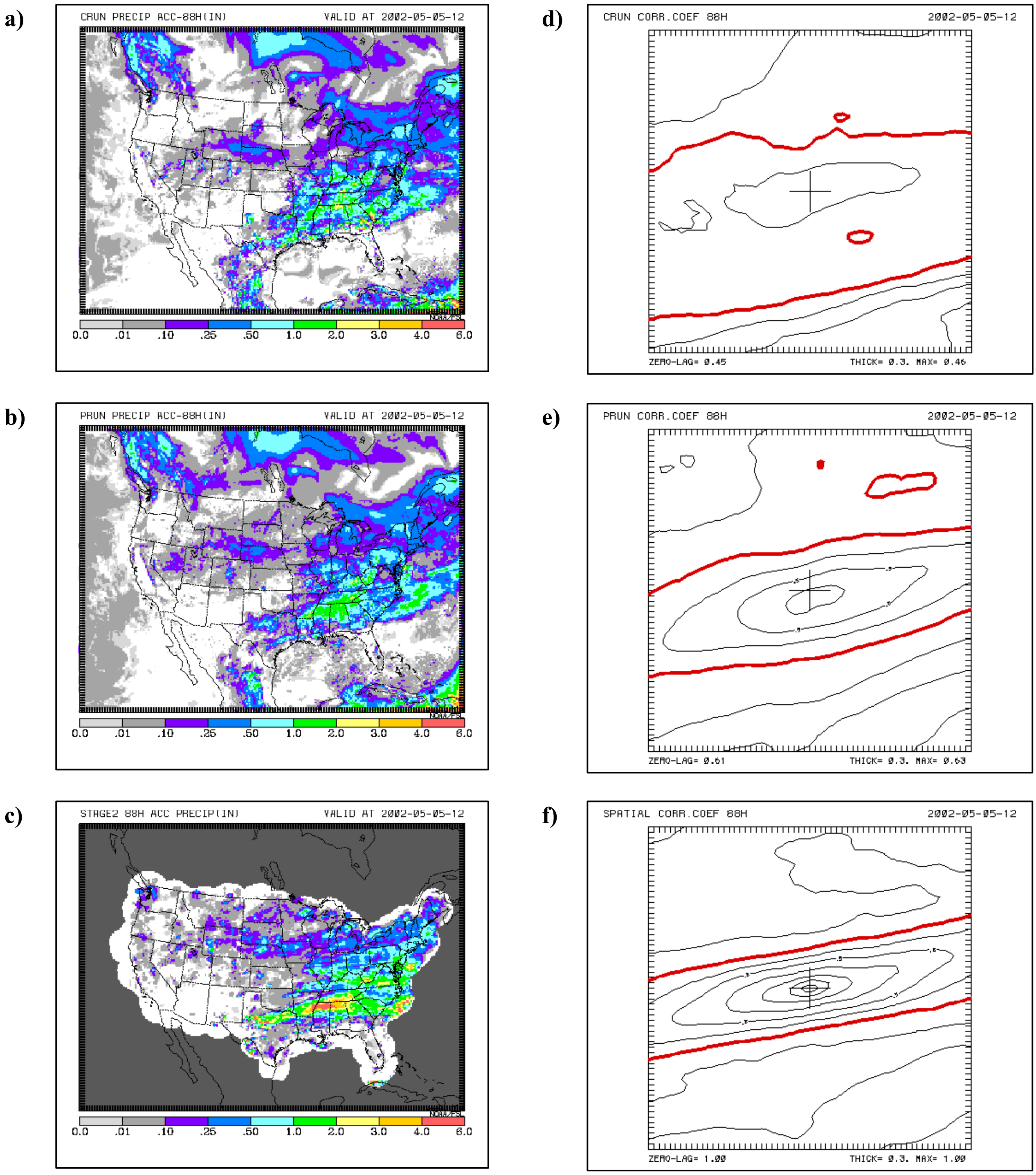

Fig 6 (left) (left) An 88-h accumulation of precipitation for the period ending 0600 UTC 28 April 2002 from (a) control run without radar reflectivity assimilation, (b) from parallel run with radar reflectivity, and (c) Stage II precipitation amounts. Forecast amounts are the sum of 88 consecutive 1-h forecasts from RUC cycles. Fig 6 (right) Spatial cross-correlation contours between Stage II QPE and forecast QPF for (d) 88-h control run, (e) 88-h parallel run, and (f) spatial auto-correlation of 88-h QPE. The maximum values are 0.63 for parallel run with radar reflectivity assimilation, and 0.46 for control. Thick contours are 0.3.

6. Acknowledgments

We acknowledge the ongoing work of the rest of the RUC development group (J. Brown, K. Brundage, D. Devenyi, G. Grell, T. Smirnova, T. Smith, and S. Weygandt) in the Forecast Research Division at the NOAA Forecast Systems Laboratory. We also thank N. Fullerton and D. Devenyi for their careful reviews of the paper. This work is supported partially by GCIP NOAA Office of Global Program, and Joint Center for Satellite Data Assimilation.

7. References

Baldwin, M. E. and K. E. Mitchell, 1997: The NCEP hourly multi-sensor U.S. precipitation analysis for operations and GCIP research. Preprints, *13th Conference on Hydrology,* Amer. Meteor. Soc, 54-55.

Benjamin, S. G., D. Devenyi, S. S. Weygandt, K. J. Brundage, J. M. Brown, G. A. Grell, D. Kim, B. E. Schwartz, T. G. Smirnova, and T. L. Smith, 2003: An hourly assimilation/forecast cycle: The RUC. Submitted to *Mon. Wea. Rev*.

Brown, J., T. Smirnova, S. Benjamin, R. Rasmussen, G. Thompson, and K. Manning, 2000: Use of mixed-phase microphysics scheme in the operational NCEP Rapid Update Cycle. *9th Conerence. on Aviation, Range and Aerospace Meteorology*, Orlando, FL, Amer. Meteor. Soc, 522-524.

Kim, D., and S.G. Benjamin, 2000: An initial RUC cloud analysis assimilating GOES cloud-top data. Preprints *9th Conference Aviation Meteorology*, AMS, Orlando, 522-524.

Kim, D., and S.G. Benjamin, 2001. An initial RUC cloud analysis assimilating GOES cloud-top data. Preprints, *14th Conference Num. Weather Prediction*, Amer. Meteor. Soc., Ft. Lauderdale, P113-115.

Smirnova, T.G., J.M. Brown, S.G. Benjamin, and D. Kim, 2000: Parameterization of cold-season processes in the MAPS land-surface scheme. *J. Geophys. Res*., **105**, D3, 4077-4086.

Rogers, R. R., and M. K. Yau, 1989: *A Short Course in Cloud Physics*, 3rd Ed. Pergamon Press, Oxford, 293 pp.

Webster, R and M. A. Oliver, 2001: *Geostatistics for Environmental Scientists*, John Wiley & Sons, 271 pp.