3DVAR and Cloud Analysis with WSR-88D Level-II Data for the Prediction of Fort Worth Tornadic Thunderstorms

Part II: Cloud analysis

Ming Hu\textsuperscript{1,2}, Ming Xue*\textsuperscript{1,2}, and Keith Brewster\textsuperscript{1}
\textsuperscript{1}Center for Analysis and Prediction of Storms
\textsuperscript{2}School of Meteorology
University of Oklahoma, Norman, OK 73019, USA

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*Corresponding Author Address:
Dr. Ming Xue,
School of Meteorology, University of Oklahoma,
100 East Boyd, Norman, OK 73019, USA
E-mail: mxue@ou.edu.
ABSTRACT

In this two-part paper, the impact of Level-II WSR-88D reflectivity and radial velocity data on the prediction of a cluster of tornadic thunderstorms are studied. Radar reflectivity data are used primarily in a cloud analysis procedure that retrieves the amount of hydrometeors and adjusts in-cloud temperature, moisture fields, and cloud fields, while radial wind data are analyzed through a 3DVAR scheme that contains a mass continuity constraint in the cost function. In Part I, we have discussed the impact of radial velocity data and mass continuity constraint. In this Part, we will study the impact of cloud analysis and modifications to the cloud analysis scheme.

The case studied is that of the 28 March, 2000 Fort Worth tornado outbreaks. The same case was studied by Xue et al. (2003) using the ARPS Data Analysis System (ADAS) and an earlier version of the cloud analysis procedure with WSR-88D Level-III (NIDS) data. Since then, several modifications to the cloud analysis procedure, including those to the in-cloud temperature adjustment and the retrieval of precipitation species, have been made. They are described in detail with examples in this Part.

Using the same assimilation and prediction system as Part I, but without radial velocity data and mass continuity constraint, experiments with different settings within the cloud analysis procedure are examined. It is found that the experiment using the improved cloud analysis procedure with Level-II reflectivity data can capture the important characteristics of the main tornadic thunderstorm more accurately than the experiment using the earlier version with Level-III reflectivity data. The contributions of different modifications to the above improvements are also investigated.
1. Introduction

This is the second part of a two-part study investigating the impact of radar data on the prediction of a cluster of tornadic thunderstorms. The importance and difficulties of using radar data in storm-scale data assimilation and forecast, and the retrieval and assimilation techniques used to determine atmospheric state variables that are not directly observed by radar, have been introduced in the first part (Hu et al. 2004, hereafter Part I).

In Part I, radar radial velocity data are analyzed via a three dimensional variational (3DVAR) analysis system to infer storm information in the wind field, while reflectivity data are used through a cloud analysis procedure to define hydrometeor fields and to make adjustments to in-cloud temperature and moisture fields. The 3DVAR analysis system used in this study is developed within the ARPS model (Xue et al. 1995; Xue et al. 2000; Xue et al. 2001) framework and documented in Xue et al (2003) and Gao et al. (2002; 2004).

The cloud analysis procedure has evolved from that used in the Local Analysis and Prediction System (LAPS, Albers et al. 1996) cloud analysis with previous modifications documented by Zhang et al (1998) and Zhang (1999). It is a part of both the ARPS 3DVAR and ADAS (Brewster 1996) analysis systems. In the experiments by Xue et al. (2003, hereafter X03), the ADAS and a previous version of cloud analysis with WSR-88D Level-III (NIDS) data were used in data assimilation to provide initial field for ARPS model to predict 28 March, 2000 Fort Worth tornadoes. Since then, several improvements have been made in cloud analysis procedure to make it more suitable for thunderstorm initialization and some of these improvements are described in Brewster (2002).
Using ARPS 3DVAR instead of ADAS as the analysis method, together with the improved version of the cloud analysis procedure, Level-II instead of Level-III radar data, and an updated version of the ARPS model, experiments in Part I studied the impact of radial velocity data on the same tornado outbreak case as studied by X03. It is found that reflectivity data has a greater positive impact on storm forecast than radial velocity with the current 3DVAR and cloud analysis procedure, although adding radial velocity data to the reflectivity data results in further improvements in the prediction of thunderstorms in this case. Those experiments clearly show that the storm information in initial temperature and hydrometeor fields added by cloud analysis with radar reflectivity data are critical for successful storm forecasts in this case. In this second part, we will examine the impact of the improved cloud analysis procedure and of each modification individually through the experiments that have the same structure as those in Part I.

The organization of this paper is as follows. In Section 2, the previous cloud analysis scheme and the modifications to it are described in detail. In Section 3, we describe the real case we used here and the design of experiments for investigating the impact of improved cloud analysis and each modification. A detailed comparison among experiments is presented in Section 4. We then summarize our results in Section 5.

2. Cloud Analysis

The cloud analysis procedure incorporates cloud reports from surface observing of Global Observing System (GOS) of World Meteorological Organization (WMO), standard Aviation Routine Weather Reports (METARs), satellite infrared and visible imagery data, and radar reflectivity data to construct three-dimensional cloud and precipitate fields. The products of the analysis package include three-dimensional cloud cover, cloud liquid and
ice mixing ratios, cloud and precipitate types, icing severity index, and rain, snow and hail mixing ratios. Cloud base, top and cloud ceiling fields are also derived. A latent heat adjustment to temperature based on added adiabatic liquid water content is applied, so that the in-cloud temperature is reasonably consistent with the water fields. More details on the package can be found in the references cited in Section 1.

The above version of cloud analysis was used by the experiments in X03. In most experiments presented here, the improved cloud analysis procedure is used to assimilate reflectivity data into the model initial field. In this section, we will introduce these modifications to cloud analysis scheme with examples from corresponding analysis experiments. For the convenience of introduction, we call the cloud analysis method used in X03 the old scheme and the modified cloud analysis method used in this paper the new scheme.

a. The analysis of precipitation species

1) Equations for defining precipitate mixing ratio from reflectivity

To emphasize the impact of radar data, satellite data and surface cloud observations are not used in the cloud analysis procedure in this paper. The reflectivity equations used by the new analysis procedure for the retrieval of three dimensional precipitation species is based on those of Smith, Myers and Orville (1975) with slight differences. The actual formula used are described in Tong and Xue (2004). Similar formulae are also used by Ferrier (1994). In this paper, the retrieval of precipitation species is the process that derives precipitation species from observed reflectivity and analysis and the radar reflectivity equations are used in the process but not the background values of the precipitation species. The reflectivity is divided into three
components due to contributions from rain, snow, and hail respectively. Each reflectivity component can be calculated by a function including the mixing ratio of corresponding hydrometer and environment variables. Based on precipitation types identified according to reflectivity and environment variables from the output of the basic analysis scheme such as 3DVAR, the equations for the reflectivity components are used to determine the mixing ratios of rainwater, snow and hail. We refer to this precipitation species retrieval scheme as the SMO scheme.

In the old cloud analysis procedure, the rainwater mixing ratio is retrieved using Kessler reflectivity equation (Kessler 1969), and snow and hail are retrieved using Rogers and Yau (1989) reflectivity formula. Hereafter we refer to this hydrometer retrieval scheme as the KRY scheme.

The SMO scheme considers more detailed cloud physics processes and should yield hydrometer fields that are more accurate than KRY scheme does.

2) The reflectivity used in the retrieval equations

In the region of the model domain covered by the radar scan volume, the new scheme classifies grid points into clear, precipitation-filled, and missing observation categories according to a threshold of reflectivity, which is an adjustable parameter and set to 10 dBZ in all experiments in this paper. A grid point with observed reflectivity greater than or equal to the threshold is treated as precipitation-filled and its precipitation species will be retrieved by the SMO scheme from the observed reflectivity. Any point with observed reflectivity that ranges from –20 dBZ to the threshold is treated as clear and its precipitation species are set to zero. The point that does not belong to above two categories falls into the missing observation category, and background values (usually
from previous forecast) are used for its precipitation species. In the KRY scheme, the threshold is fixed at 0 dBZ. The points with reflectivity greater than 0 dBZ are considered to be precipitation-filled and all other points are treated as precipitation-free.

For the area that is outside the observed range of the radar, both schemes use background values for the precipitating hydrometeors. For the point below the first radar elevation scan, the old scheme sets the precipitation species to zero while new scheme uses the background value that is further adjusted to disallow the sum of rain, snow and hail mixing ratios to exceed the maximum value of the same in the column above.

Figure 1 shows the retrieved precipitation species by the old scheme (left column) and the new scheme (right column) from the same radar observation and the environmental analysis. The old scheme gives much more hail and rain but less snow than new scheme. These figures illustrate that the old scheme is designed for warm rain that has not much vertical extent. In the rain field determined by the new scheme, the large values under the first radar tilt come from the background.

3) Assigning the final values of precipitation species

In general, analyses for numerical weather prediction are calculated as a sum of background values and analysis increments due to observations, weighted by factors related to the error variances of background and observation. Precipitation fields are, however, not continuous variables therefore require a different scheme to determine the final analysis quantities, reconciling the background quantities and the observations. In the old scheme, the final analysis of precipitation species is the greater of the background and observed quantities. This was a legacy from LAPS which had been developed using a mesoscale Rapid-Update-Cycle (RUC) model forecast as the background field, not a
storm-scale model forecast. In new scheme, the analysis takes the values retrieved from the observations, except in the area of missing observations and outside the radar observing range, where background values are then used for the precipitation mixing ratios. This approach is more appropriate when use storm-scale forecasts as the background as we do inside assimilation cycles. Choosing the observation over the background is based on the belief that radar observations of precipitation are much more reliable than that predicted by a numerical model. Furthermore, at the storm scale, reliable information about the background error, especially that of precipitation fields, is generally unavailable.

We demonstrate the effect of the above procedure, by examining the analyses for a situation using a 3-km 10-minute ARPS forecast as the background field and radar data at 2250 UTC on 28 March, 2000 in the Fort Worth, Texas area. The final analysis of precipitation species by the old scheme is plotted in Fig. 2. Compared to the retrieval (Fig. 1, left column), it can be seen that with the old scheme the background values dominate the final analysis for all three species. The reflectivity fields calculated from the precipitation mixing ratios of the background, the final analysis of the old scheme and new scheme are plotted in Fig. 3. We can see that analyzed reflectivity from the old scheme largely reflects the background, while the analyzed reflectivity using new scheme shows many detailed structures inside the storms.

\[ b. \textit{The cloud water and cloud ice} \]

To estimate cloud water and cloud ice, the adiabatic liquid water content (ALWC) is estimated by assuming moist-adiabatic ascent from cloud base to cloud top. Then a reduction is applied to the ALWC to account for entrainment. In old scheme, the curve of
reduction was determined from field data that was collected largely from isolated towering cumulus clouds. In a case with supercell thunderstorms or widespread thunderstorms, the clouds have much larger vertical extent and less entrainment in the center of storm cells. So a new entrainment curve is devised for the new scheme to provide greater cloud water and cloud ice content. Fig. 4 shows analysis of cloud water and cloud ice using the old curve (left) and the new curve (right) with reduced entrainment. The increased cloud mixing ratios are quite evident. In the current 3-km grid system, we have noticed that the initial cloud water and cloud ice are sufficient to sustain the cloud and precipitating convective cells for 10 to 15 minutes into the forecast and the continued sustenance requires cloud water and cloud ice be generated by continued condensation of moisture, generally due to moist-air lifted from the boundary layer.

c. In-cloud thermal adjustment

In the old scheme the incremental buoyancy added due to the added cloud water and precipitation is calculated from the latent heat released by the incremental cloud water and ice. In new scheme, a moist-adiabatic temperature profile with the same entrainment factors as applied to the cloud water, is used to adjust temperature after the determination of cloud and precipitation content. The new in-cloud temperature adjustment scheme is more consistent with the physics of a convective storm because it reflects the temperature change in an ascending bubble of moist air. The typical temperature increments from the adjustments of new and old schemes are plotted in Fig. 5. The profile of horizontally averaged temperature increments show that the new method heats atmosphere through a greater depth than the old method, while the old scheme acts to warm the atmosphere more in middle and low layers because the added cloud water
and ice tend to be concentrated in these layers (Fig. 5a). The difference in the temperature increment between the two schemes at 4.5 MSL in Fig. 5b reflects the main structures of observed reflectivity (not shown).

3. ARPS data assimilation and forecast systems and design of experiments

The same tornadic thunderstorm outbreak that was studied in Part I is used here to examine the impact of modifications to cloud analysis procedure. In this case, an F2 (maximum winds 51 m s\(^{-1}\) to 70 m s\(^{-1}\)) tornado struck downtown Fort Worth Texas (TX), at around 6:15 pm LST 28 March, 2000 (0015 UTC 29 March). The tornado vortex developed directly over the city, descended, and stayed on the ground for at least 15 minutes. A second tornado from the same cell touched down in south Arlington, some 25 kilometers east of Fort Worth, about 30 minutes later, at around 6:45 pm LST 28 March, 2000 (0045 UTC 29 March).

Using the same simulation system as Part I, four prediction experiments are conducted herein to study the impact of the improved cloud analysis procedure. In these experiments, two levels of one-way nested grids are used, with horizontal grid spacing of 9 and 3 km. The two grids cover areas of 1000 ×1000 and 450×300 km\(^2\), respectively. Full model physics are employed in both grid forecasts. In the 9-km grid, a 12-hour model forecast is started from a single 3DVAR analysis at 1800 UTC 28 March using lateral boundary conditions from the National Center for Environmental Prediction (NCEP) Eta 1800 UTC forecasts at 3-hour intervals.

Different from the control experiment in Part I, in this part, only reflectivity data are employed in the assimilation cycles of control experiment, CNTL, at the 3-km resolution to investigate the use of cloud analysis. Similar to Part I, the WSR-88D full-
volume (Level-II) reflectivity data are used in 10-minute intermittent assimilation cycles that begin at 2200 UTC and continue for one hour. The 3DVAR analysis is used to analyze model state variables in data assimilation but no radial velocity data are employed in its wind analysis. The 3-km forecast, with the model settings same as Part I, starts from the assimilated initial condition at 2300 UTC and ends at 0200 UTC 29 March.

The control experiment of X03 is repeated in this part for comparison (listed as experiment X03 in Table 1). The differences between X03 and other experiments are compared in detail in Part I. The main aspects include the analysis method used in data assimilation, the data sources used in cloud analysis procedure, and the interval of assimilation cycles.

Based on the control experiment, CNTL, three experiments, CTLH, CMAX and CKRY are performed to examine the impact of different schemes of in-cloud temperature adjustment, final precipitation species assignment rules and the retrieval of precipitation species values in the old and new cloud analysis procedures (Table 1).

4. Results of forecast experiments

In this section, the forecast results from experiments CNTL and X03 are first analyzed to investigate the impact of the new cloud analysis procedure and Level-II WSR-88D reflectivity data. The impacts of each modification in the new cloud analysis procedure are then examined by comparing assimilation and forecast results of all five experiments.
a. Radar observation

Observed reflectivity at elevation 1.45° scan from Level-II data of Fort Worth radar (KFWS) at 15-minute intervals for 1 hour starting from 0000 UTC 29 March are plotted in Fig. 6. This hour covers the critical period for forecast in which two tornadoes touchdown in Tarrant County (one at 0015 UTC at Forth Worth and one at 0045 UTC near Arlington). Tarrant County is highlighted by the bold rectangle in the figure. Downtown Fort Worth and Arlington are marked by black dots in Fig. 6a.

Following the description given in Part I, five individual thunderstorms can be identified around Forth Worth from the observed radar reflectivities at 0000 UTC 29 March (Fig. 6a). Storm A is the storm that spawned the downtown Forth Worth tornado 15 minutes hence and the Arlington tornado 45 minutes hence. Storm B followed Storm A from the west. It approached Storm A from 0000 UTC to 0045 UTC (Fig. 6a-d) and then merged with Storm A to form a combined storm that we re-label as F (Fig. 6e). Storms C and C' formed after the assimilation cycles end, propagated toward Storm A from the south and also merged into Storm A (Fig. 6) at about 0100 UTC. Storm D is located initially near the northeast corner of Hill County and later propagated northeastward into Ellis County. Storm D formed during the assimilation cycles and remained strong throughout the hour (Fig. 6). It is a significant challenge for the data assimilation and model forecasting system to accurately forecast these individual storms and their complex interactions.

b. Results of experiments CNTL and X03

Predicted reflectivities (computed from precipitation species using radar reflectivity equations) at an emulated 1.45° tilt (corresponding to the elevation angle of
The radar observed reflectivity in Fig. 6) derived from CNTL and X03 are plotted in Fig. 7. The plots start at 0000 UTC 29 March, which is 2 hours after the data assimilation cycle is started and 1 hour after the forward forecast initial time, and end at 0100 UTC 29 March at 15-minute intervals. For convenience of comparison, the left column of Fig. 7 shows results of X03, in which the old cloud analysis scheme with Level-III reflectivity is used, while the right column shows the counterparts from CNTL, whose assimilation cycles employ the new cloud analysis with Level-II reflectivity.

At 0000 UTC 29 March, the one-hour forecast of CNTL exhibits reasonable structures of the storms around Fort Worth (Fig. 6a, Fig. 7b) but with some position errors. Predicted Storm A lags the observation about 20 km. Predicted Storm B only shows as a weak echo and lags observation about 20-25 km. The model produces Storm C with a northward displacement of about 5 km and does not produce Storm C'. Considering that little information on Storms C and C' was provided by the assimilation cycles directly, it is encouraging that the model produces Storm C by itself at this time.

The model produces an accurate forecast of Storm D, but at the same time, it generates a spurious storm, D', which split from Storm D in the first hour of the forecast and moves north into the southeast corner of Tarrant County. Another spurious storm appears southwest of Storm A and is labeled as A'. Comparing these storms to their counterparts in X03 (Fig. 7a), they are stronger than those in X03 except for spurious Storm D'. At this time, X03 gives much better position forecast for both Storms A and B than CNTL does. However, the forecast of X03 misses Storms C and C', and produces a spurious storm, A', southwest of Storm A.
Fifteen minutes later, at 0015 UTC, is the time of first tornado touchdown, in downtown Fort Worth. Experiment CNTL correctly predicts tornadic Storm A strengthening and approaching Fort Worth from the west, although the forecast reflectivity maximum of Storm A is still a little behind the observation (Fig. 6b and Fig. 7d). Predicted Storm B remains weak and lags the observation about 25 km. Predicted Storm C is located midway between observed Storms C and C'. Storm D is well reproduced by CNTL and the spurious Storm D' that appeared earlier has dissipated by this time. The spurious Storm A' has grown and is still southwest of Storm A. In comparison, the storms in X03 moved eastward too quickly in the period from 0000 to 0015 UTC and the reflectivity maximum of Storm A has completely passed downtown Fort Worth (Fig. 7c). A weak echo at the center of the western boundary of Johnson County gives the only hint of observed Storm C in the Experiment X03 forecast. Just to the west of predicted Storm C, spurious Storm A' has developed into a long band-shaped echo connected with Storm A and subsequently sweeps through the weak Storm C. Unlike CNTL, spurious Storm D' in X03 remains as a strong northbound storm.

At 0030 UTC, in the CNTL forecast, Storm A is nearly collocated with the observed cell except that it extends too much in the north-south direction and has two maxima reflectivity centers (Fig. 6c and Fig. 7f). Its shape does suggest an inflow notch on its southeastern flank. At this time, Storm B is not identifiable as a separate storm, though the southwestern quadrant of Storm A and the northeastern corner of Storm A' overlay the position of Storm B. Predicted Storm C appears as a weak echo that covers location of observed Storm C and C'. There is reason to believe the CNTL forecast is a bit fast with the merger of cells that occurs in Tarrant County. Storm D is well
reproduced except that it moves a little faster than observation, and spurious Storm A' still exists with a strong reflectivity center. In the X03 forecast, intense reflectivity composed by Storm A and A' is found extending from Storm A in the northeast corner of Tarrant County through the southwest corner of the county and reaching the center of Hood County (Fig. 7e). This may be a malposition of Storm A – representing a 30 km displacement, possibly due to a merger with the spurious Storm D'.

At 0045 UTC, a second tornado struck just south of Arlington. In the CNTL forecast, the main characteristics of Storm A are successfully reproduced (Fig. 6d, Fig. 7h). The predicted southern reflectivity maximum of Storm A has intensified and is just south of Arlington. Together with northern reflectivity maximum of Storm A and the westward-extending part of Storm A, the area of predicted Storm A covers the bulk of the combined area of observed Storms A, B and C. At this time, isolated spurious Storm A' is weak. Predicted Storm D is still in a position a few km southeast of the observed cell. In the X03 forecast, the Storm D' has merged with Storm A and makes the later skip into the center of Dallas County (Fig. 7g). The northeast part of Storm A' is at the same area as the south center of Storm A in CNTL and nears south Arlington too.

By 0100 UTC, observed Storms A, B and C had merged into one storm F (Fig. 6e). In CNTL run (Fig. 7j), the location of Storm A corresponds to the correct location of observed storm F, while in the X03 forecast (Fig. 7i), Storm A has led the observed Storm F over half a county (35 km) and Storm A' covers part of Storm F, but its center deviates from the main part of observed F by 15 km. The position forecast for Storm D in CNTL is also more accurate than that of X03 at this time.
The surface wind and temperature fields from CNTL and X03 at the time of the tornadoes are plotted in Fig. 8. At time of the downtown Fort Worth tornado, or about 0015 UTC, CNTL predicts areas of strong convergence along the gust front produced by tornadic Storm A approaching downtown Fort Worth from the northwest (Fig. 8b), while in experiment X03, the convergence coincident with the gust front of Storm A is much weaker and has passed downtown Fort Worth (Fig. 8a). At the time of the Arlington tornado, 0045 UTC, the gust front and low-level convergence related to Storm A are still strong and approach south Arlington in the CNTL run (Fig. 8d). In X03 (Fig. 8c), the gust front of Storm A is weaker and Storm A has moved east of Tarrant County. Almost the entire county is covered by the cold pool of Storm A at this time.

From the above comparison, it is found that using the new cloud analysis procedure with Level-II reflectivity data through assimilation cycles improves the prediction of the tornadic thunderstorm in this case. In the CNTL run, the tornadic thunderstorm A, appearing with strong reflectivity with strong low-level convergence centers, approaches and passes downtown Fort Worth and Arlington around the times of tornado occurrence, while in X03, the reflectivity center of Storm A and the related gust front moved too fast and have obvious locations errors during the tornado touchdowns.

Similar to Part I, the equitable threat scores (ETS, Schaefer 1990) of predicted reflectivity fields at the 1.45° elevation level for the 5, 15, 30 and 45 dBZ thresholds are calculated and plotted in Fig. 9. We can see that the scores decrease quickly in first hour of forecast then increase in second hour for all thresholds, which reflects the adjustments of initial storms in the first hour of forecast. It can be seen that all scores are better for CNTL than for X03 from 0030 UTC to 0100 UTC, in agreement with the earlier
subjective assessment of the forecast of cell centers. Our subjective analysis does suggest that the forecast of CNTL is superior at 0015 UTC for Storm A, however, the scores for the entire domain do not reflect this. The reason is that both CNTL and X03 have some phase errors in the predictions of Storms A, B, and C, and also contain some spurious storms at this time. The disagreement between the ETS at 0015 UTC and our subjective analysis suggest that the ETS for the entire domain is not necessarily a good measure for evaluating forecasts containing discrete features, again, for which phase errors can have a significant impact on the calculated scores. Verification of discrete features remains an active area of research and our use of the equitable threat score here is only intended to provide some degree of objectivity.

\hspace{0.2in}c. Sensitivity to details of cloud analysis

To identify the impact of each modification in cloud scheme on the results of assimilation and forecast, three experiments are done: 1) CTLH, in which in-cloud temperature adjustment is based on latent heat conversion instead of moist adiabatic temperature profile, 2) CMAX for which the quantities of the precipitation species are determined by the maximum value of background and retrieval instead of the observation-based retrieval values alone, and 3) CKRY, which uses the KRY scheme instead of the SMO scheme to retrieve the quantity of each precipitation species. All other options in these experiments are the same as the control experiment, CNTL. Comparison among these experiments will give us some insight on the effect of the new cloud analysis procedure.
1) Sensitivity test results

In Part I, it was found that information on the storm-scale is largely added to the system via the cloud analysis in the data assimilation cycles. Modifications to the cloud analysis will directly influence results of the assimilation and the ensuing model forecast.

Reflectivity fields from the assimilation output of the five experiments mapped to the elevation $1.45^\circ$ scan of radar KFWS are plotted in Fig. 10 along with the corresponding observed radar echoes. In the initial field of CNTL, the storm structures look very much like the observed reflectivity, though the interpolation scheme and cloud processing make the features smoother than the observed ones (Fig. 10a, b). Keeping in mind that CNTL uses the retrieved quantity of the precipitation species directly in the analysis, it is fully expected that the assimilation reflectivity and observation match each other very well. In contrast, the initial reflectivity field in X03 only gives the basic structure of storm cluster and loses many details of storm cells (Fig. 10c). Experiment CTLH has the identical initial reflectivity field to that of CNTL in the area near the radar (Fig. 10d), but has stronger reflectivity maxima than their counterparts in CNTL in the area distant from the radar because the two experiments have different mid-level temperature fields as depicted in Section 2c. Experiment CKRY uses simple radar reflectivity equations to retrieve precipitation species, so its result is a little smoother than that of CNTL (Fig. 10e). From the initial reflectivity field of CMAX, the influence of the background values of the precipitation species can be seen clearly in Fig. 10f because in this case the maximum value of background and retrieved precipitation species is used for the analysis values, and the background reflectivity is generally greater than the observations at this time through much of the domain.
The surface wind and temperature fields from all five experiments and from the background before 3-km analysis are plotted in Fig. 11. In this figure the storm-related gust fronts and cold pools are found in the initial fields of all five experiments. As was noted in the forecasts of reflectivity, the CNTL run (Fig. 11b) induces more details of storms in its initial field than X03 (Fig. 11c). In the initial surface wind and temperature fields from CTLH, CKRY, and CMAX (Fig. 11d, e, f), only CTLH has large differences from CNTL; its appearance is more like X03. Both CTLH and X03 underestimate the strength of the cold pool and gust front related to Storm A (Fig. 10a). That indicates the formation of cold pool and gust front is very sensitive to the choice of temperature adjustment scheme, presumably through the direct effect of the latter on storm intensity.

The strength of the updraft is an important indicator for the vigor of a thunderstorm. Fig. 12 is the cross section of vertical velocity, w, fields along a line through Storms A and B (Fig. 10a). In X03, the updraft related to Storm B is weak and there is no sign of the existence of Storm A (Fig. 12a) in this cross-section, while in CNTL (Fig. 12b), two large updraft centers associated with Storms A and B are found. It shows that storms have been built up through assimilating Level-II reflectivity data by the new cloud analysis procedure. The vertical velocity fields from CMAX, CKRY and CTLH reflect varied impacts of each modification (Fig. 12c, d, e). Each of them has just one strong updraft center and one weak updraft center in the initial w field. Comparing Fig. 12 to the corresponding surface wind and temperature fields (Fig. 11), it is found that the vertical motion of Storm A is strongly related to the strength of its the surface cold pool and gust front.
2) Forecast Results

In the above subsection, we have seen that assimilation results are obviously affected by modifications to the cloud analysis procedure. In this subsection, forecasts initialized from the results of assimilation are compared so as to make further inferences on the effects of these modifications. Fig. 13 shows the predicted reflectivity mapped to the 1.45° elevation level of KFWS radar from CTLH, CMAX, and CKRY at the time of the tornadoes. The surface wind and temperature fields from the same experiments and times are plotted in Fig. 14.

Since CMAX, CKRY and CTLH each has only one aspect in their cloud analysis procedure that is different from that of CNTL, the main characteristics of their predicted storm cluster are similar to that of CNTL at the time of the downtown Fort Worth tornado (Fig. 13a, c, e, Fig. 7d). Focusing on the details of Storm A, it is found that Storm A in CKRY and CTLH has the same shape and position as in CNTL, while the storm moves a little faster in CMAX than in CNTL. The gust fronts related Storm A tell the same story as the reflectivity fields. That is, the gust fronts of Storm A in CKRY, CTLH, and CNTL (Fig. 8b, Fig. 14c, e) are in similar positions, while that in CMAX moves faster (Fig. 14a) than that in the other experiments. All three experiments have spurious Storms A' and D' appearing in the forecast at this time (Fig. 13a, c, e).

By 0045 UTC, the differences among CMAX, CKRY, CTLH and CNTL have increased (Fig. 13b, d, f, and Fig. 7h). Storm A in CMAX has obviously led its counterpart in CNTL and connected with spurious Storm D'. It will propagate into the center of Dallas County in next 15 minutes of the forecast as Storm A does in X03. The northern part of its gust front in CMAX has reached the east boundary of Tarrant County.
and the southern part is approaching to the southeast corner of the county (Fig. 14b). Although Storm A in CKRY and CTLH has the same position at 0015 UTC, it propagates in different directions in these two experiments during the following half an hour. In CKRY, Storm A moves southeast to the center of Tarrant County and lags Storm A in Experiment CNTL. In Experiment CTLH, Storm A propagates northeast and has run out of Tarrant County from its northeast corner. In surface wind and temperature fields of CKRY and CTLH (Fig. 14d, f), the clod pool and gust front of Storm A follow the same motion direction and reach the same position as the reflectivity.

Another big difference among these experiments at 0045 UTC is the behavior of spurious Storm D'. It remains as a strong isolated echo in CKRY (Fig. 13d), connects with Storm A in CMAX (Fig. 13b), and has merged into Storm A in CTLH (Fig. 13f) and partly account for the fast motion of Storm A in that experiment. The spurious Storm D' does not exist after 0015 UTC in the forecast of CNTL (Fig. 7), while it merges with Storm A at 0030 UTC in the forecast of experiment X03 and causes large location errors of Storm A at 0045 UTC.

The comparisons above show that adjusting in-cloud temperature based on a moist-adiabatic profile and choosing the values of retrieved precipitation species over those of background in the new cloud analysis procedure act to slow down the motion of predicted tornadic Storm A during the period of the tornado occurrence. These two modifications, together with the use of SMO scheme to retrieve precipitation species, contribute to the erasure of spurious Storm D' and then further avoid the erroneous acceleration of Storm A found in the X03 forecast. So the CNTL with all the
modifications of the new cloud analysis procedure gives the best forecast for the tornadic thunderstorm during the critical tornado outbreak period in this case.

5. Summary

In this second part of our two-part paper, we focus our discussion on the new cloud analysis procedure used with the WSR-88D Level II reflectivity data. Five experiments are conducted to investigate the impact of three modifications to the cloud analysis procedure on the forecast of thunderstorms in Fort Worth tornado case.

Starting from an initial condition that assimilates Level-II reflectivity data through the new cloud analysis procedure, the control experiment CNTL successfully reproduces the evolution of the most significant thunderstorms in the Fort Worth tornado case. The forecast shows a storm with high reflectivity, strong gradients in reflectivity, and a gust front with areas of strong convergence approaches and passes through downtown Fort Worth and Arlington around the time of the tornado occurrences. Comparing to an earlier experiment, X03, that used an earlier version of the cloud analysis with Level-III reflectivity data in the assimilation cycles, the experiment with all the recent modifications to the cloud analysis, CNTL, shows reductions in both timing and location errors for the main tornadic thunderstorm.

The analysis shows that the storm status in the initial field and the evolution of the storm in the forecast can be affected by each individual modification in the cloud analysis scheme. It is found that adjusting in-cloud temperature based on a moist adiabatic profile and choosing retrieved quantities of the precipitation species over background values in cloud analysis can slow the movement of storms in this case and improve the forecast for the tornadic storm. These two modifications, and the use of the SMO scheme to retrieve
precipitation species, work together to prevent a spurious storm from appearing in the forecast.

Adding hydrometers and adjusting the in-cloud temperature and moisture field in the model initial fields are expected to reduce the spin-up problem in the forecast. From the experiments in this study, the forecast storms still have an adjustment period when the model forecast begins using an initial field from the current cloud analysis procedure. This indicates that there still exist some inconsistencies between the cloud analysis and the model microphysics and cloud dynamics. Some of the adjustment may be handled by use of the existing incremental analysis updating procedure (IAU) in ARPS in a 5-10 minute pre-forecast application of IAU. More investigation on the nature of this adjustment are needed to further improve the cloud analysis procedure.

The conclusions in this paper are based on the Fort Worth tornado case along. We have collected data for several other severe weather outbreaks and will simulate them with the same assimilation and forecast system to investigate the issues of this paper further. A recent study of Dawson and Xue (2004) on the impact of mesoscale data and cloud analysis on the forecast of a pre-existing mesoscale-convective system (MCS) finds significant positive impact of cloud analysis that lasts as long as 12 hours, although in that case, the MCS still forms in the model even with interpolated Eta analysis, but with significant time delay.

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