# A Real Case Study of Using Cloud Analysis in Grid-point Statistical Interpolation Analysis and Advanced Research WRF Forecast System

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## 1. Introduction

Moisture spin-up problem is caused by the missing or unbalanced building of precipitation systems in the initial field which can significantly delay the development of the systems at the early stage of subsequent model forecast. It is one of critical problems faced by the short-term forecast (nowcast) and high-frequency data assimilation that intend to capture high-impact precipitation systems. To eliminate the problem, accurate initialization of temperature, moisture, and hydrometer disturbances related to a precipitation system is critical. However, these important disturbances are missed by most of analysis systems because of the lack of direct observations for hydrometer fields and the missing observations of mescoscale weathers by routine observation systems. Currently, cloud and precipitation information is mainly included in surface (METAR), satellite, and radar observations, which can be used to retrieve hydrometers related to a cloud or precipitation system and to adjust corresponding temperature and moisture disturbances.

In the Center for Analysis and Prediction of Storms (CAPS), a semi-empirical complex cloud analysis procedure was developed within the Advanced Regional Prediction System (ARPS, Xue et al. 1995; Xue et al. 2000; Xue et al. 2001) to adjust in-cloud temperature, moisture, and hydrometers in the initial fields according to the cloud and precipitation observations by METARs, satellite, and radar. The ARPS cloud analysis has evolved from that used by the Local Analysis and Prediction System (LAPS, Albers et al. 1996) with previous modifications documented by Zhang (1999) and Brewster (2002). Recently, this cloud analysis procedure was implemented in the assimilation of Weather Surveillance Radar-1988 (WSR-88D) LEVEL-II reflectivity data to simulate several tornadic thunderstorms at a horizontal grid spacing of 3 km (Hu and Xue 2006; Hu et al. 2006) and it is found that the system can effectively intrigue storms during data assimilation period and significantly improve the short-term forecast for the tornadic thunderstorms.

Because of these positive impacts of the cloud analysis, it is useful to study its effects in the operational data analysis and model forecast system for the possible operational implement of the procedure. In this study, the ARPS cloud analysis procedure was used in the Grid-point Statistical Interpolation (GSI, Wu et al. 2002) Analysis and the Advanced Research WRF Forecast (WRF-ARW, Skamarock et al. 2005) System. Both the GSI and WRF-ARW are proposed successors of current operational systems in the near future. In this study, a 9-km horizontal grid spacing was used in the analysis and forecast because the operational numerical prediction system with single digital horizontal resolution becomes reality in the next few years with the acquisition of a massively parallel computer system in the National Centers for Environmental Prediction (NCEP) (Mass et al. 2002).

The organization of this paper is as follows. In section 2, the 23 May 2005 central great plain storm cluster case and the design of experiment for studying the impact of the cloud analysis in the operational framework are introduced. A detailed comparison among experiments is presented in section 3 and the results are summarized and discussed in section 4.

## 2. 23 May 2005 Central Plains Storm Cluster Case and Design of Experiments

By 0000 UTC 23 May 2005, a stationary front was formed in the north Oklahoma and Arkansas area and a large CAPE and Storm relative helicity (SRH) shear center was formed near Oklahoma-Kansas border. At 0300 UTC, two convective cells initiated at right north of Oklahoma-Kansas border and more cells initiated during the next two hours. By 0500 UTC, an NW-SE elongated storm cluster was formed in the area ranging from southeastern Kansas to southwestern Missouri. The storm cluster grew quickly from 0500 to 0900 UTC and then began to decay. The entire cluster dissipated by 1300 UTC. It caused many big hails and high winds in southeastern central plains.

Figure 1 shows the composite reflectivity combined from observations of 6 radars around the storm cluster at 0600, 0900 and 1200 UTC of 23 May 2005. At 0600 UTC, the storm cluster was in its mature stage and several strong cells distributed in the area covering southeastern Kansas, southwestern Missouri, and northeastern Oklahoma (Fig. 1a). From 0600 to 0900 UTC, the storm cluster moved toward east-southeast and mainly organized by three main cells at the end of the period (Fig. 1b). Two of them were oriented SW-NE and located at the northwest of Arkansas and the northeast of Oklahoma, respectively. The third one was slightly weaker and was at the northern border of Oklahoma. In the next 3 hours from 0900 UTC to 1200 UTC, the entire storm cluster continued moving southeastward but entered decay stage. By 1200 UTC, only a few small cells left at the northeast of Oklahoma (Fig. 1c).

This study is to investigate the impact of the ARPS cloud analysis on the storm forecast when it is used in the operational framework. The GSI analysis at 0600 UTC 23 May 2006 is used as background of the cloud analysis, and the WRF-ARW model is used to forecast the evolution of the storm cluster from 0600 to 1200 UTC. A 9-km horizontal grid spacing and 30 vertical levels with the top near 50 hPa are used in the simulation. The cloud analysis is conducted in the ARPS framework with the background interpolated from 0600 UTC GSI analysis. Two experiments, which are referred as NoCLD and CLD respectively, are completed to study the impact of the cloud analysis. In experiment NoCLD, the initial field is interpolated directly from the GSI analysis with conventional observation data, while in experiment CLD, the initial field includes the cloud analysis with radar reflectivity data. The only difference between them is if the cloud analysis is used to generate the initial field.

## 3. Experimental Results

In this section, the impacts of the cloud analysis on the initial fields and forecast are evaluated. Firstly, the differences between the initial fields of experiments CLD and NoCLD are analyzed; then, the evolution of the predicted storm cluster from experiments CLD and NoCLD are described and compared; finally, the individual cells in the 5 hours forecast of experiment CLD is evaluated by comparing to the corresponding observation.

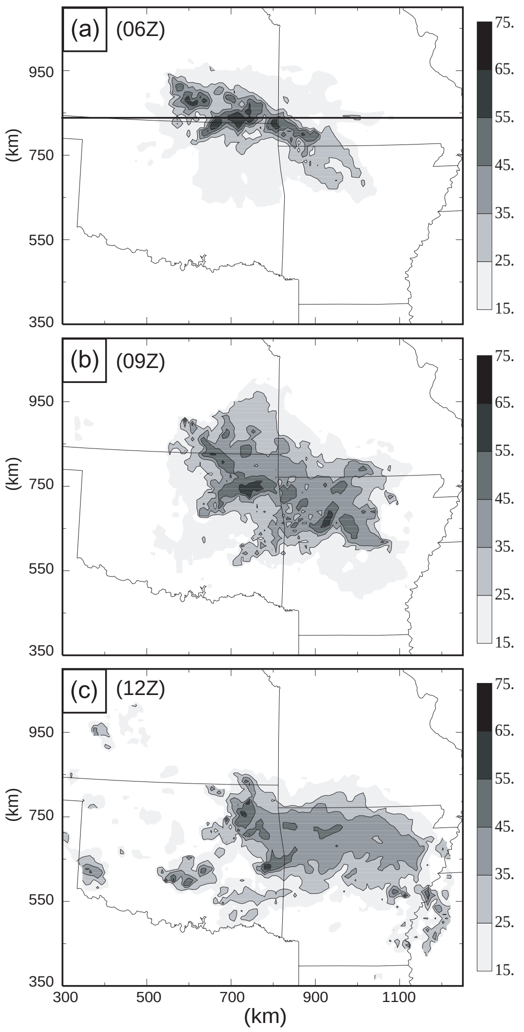


Fig. 1 Composite reflectivity combined from observations of KSRX, KVNX, KTLX, KSGF, KINX, and KLZK radar at around 0600, 0900, 1200 UTC 23 May 2005. The domain shown represents the portion of the 9-km grid between 300 and 1250 km in the east-west direction and from 350 to 1050 km in the north-south direction

### 3.1. Effects of Cloud Analysis on Initial Fields

The ARPS cloud analysis can adjust in-cloud temperature and moisture fields, and add hydrometers into initial fields. The detailed description of the ARPS cloud analysis procedure and its effects can be found in the documents listed in the introduction and here the effects of the cloud analysis in this case are shown in Fig. 2. From observed reflectivity field, several storm cells were distributed between 500 and 1000 km at 0600 UTC (Fig. 2a). The strongest cell was at around 700 km and had penetrated through the tropopause. According to the reflectivity, the cloud analysis vertically adds cloud water in the middle and low level of troposphere between 3 and 8 km and cloud ice in much higher level (Fig. 2c and d). Horizontally, the cloud water is much broader than cloud ice because the latter is mainly within the domain of the strongest cell. Similar to the cloud ice, snow is mainly added in the height above 5 km and within the range of the strongest cell (Fig. 2e). Both rain and hail only concentrate on the low troposphere, but they have different horizontal distributions: hail is added only within the strongest cell and rain has much broader distribution (Fig. 2 f and g). Apparently, the main distribution features of hydrometers fields in a storm have been analyzed into the initial field by the cloud analysis. Considering the latent heating in the updraft of storms, a positive temperature perturbation is added in the cloud and precipitation area based on an adiabatic temperature profile and the effect of this in-cloud temperature adjustment can be seen in Fig. 2b. These temperature increments affect most of reflectivity area above 4 km and have a maximum value of 8 K. They can balance the negative buoyancy of hydrometers and keep storms sustaining in the subsequent forecast.

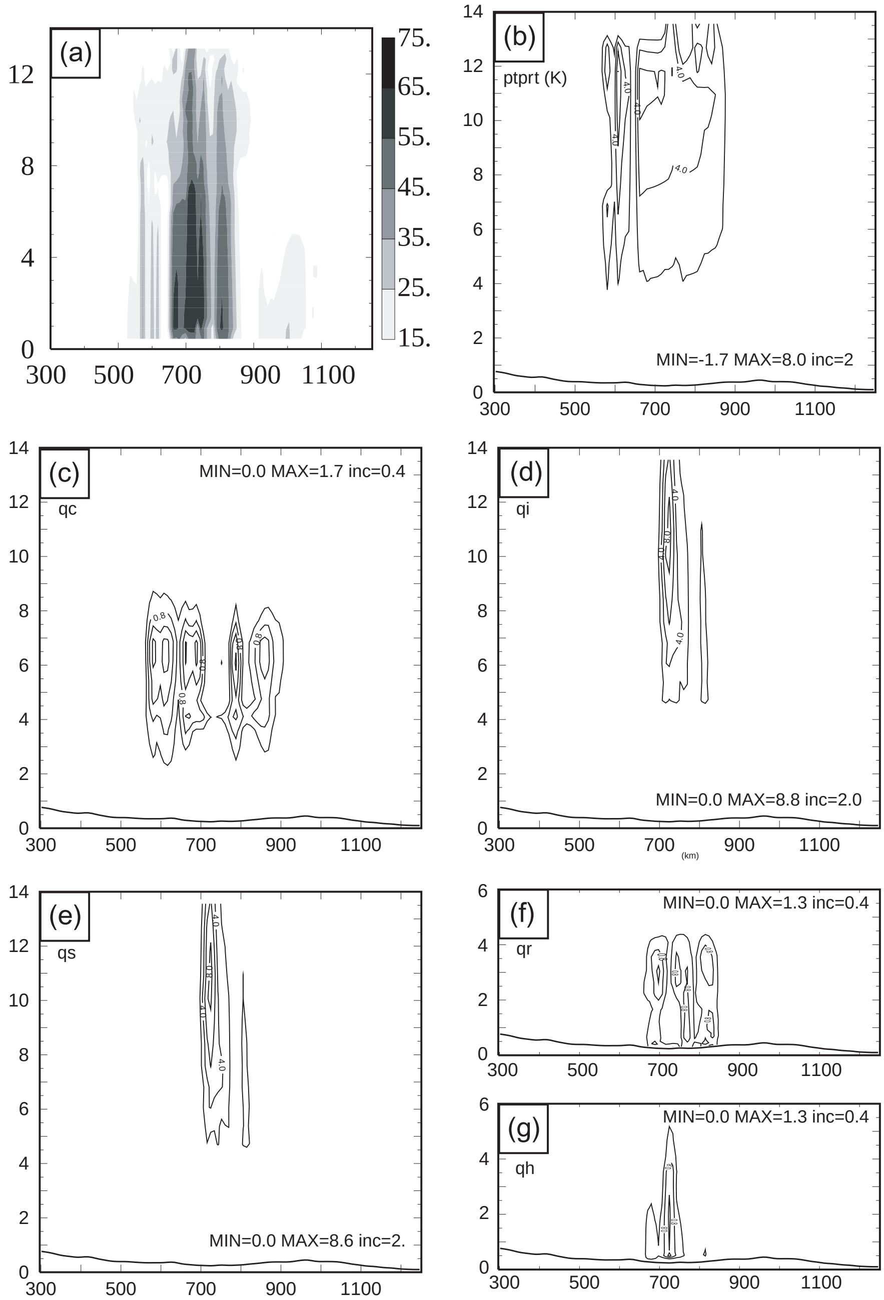


Fig. 2 X-Z cross sections along the line shown in Fig. 1a. Variables of each panel are observed reflectivity field in dBZ (a), cloud analysis increment of in-cloud temperature in K (b) and hydrometers, which are cloud water (qc), cloud ice (qi), rain (qr), snow (qs), and hail (qh), in g $kg^{-1}$. The x and z coordinates is distance in kilometer from the west boundary and bottom of the simulation domain. The numbers in each panel are the maximum (MAX), minimum (MIN), and contour increment (Inc).

### 3.2. Evolution of Predicted Storm Cluster

The previous analysis shows that some aspects of the storm cluster have been built up in the initial field by the cloud analysis. In this subsection, the subsequent 6 hours forecast of CLD and NoCLD are compared to investigate the impact of the cloud analysis on the forecast. Composite reflectivity fields of 3 and 6 hours forecast are plotted in Fig. 3 for the experiments CLD (right column) and NoCLD (left column).

When the cloud analysis with radar reflectivity is used, the 3 hours forecast of CLD captures the main characteristics of the observed storm cluster (Fig. 1b, and Fig. 3b). Like the observed one, the predicted storm cluster is located in the NW-SE elongated area from southeastern Kansas to northern Arkansas with several strong cells in it. The next 3 hours forecast predicts the individual cells propagating southeastward quickly but the entire cluster only moving slight to the southeast, which also reflects the features of the observed storm cluster motion (Fig. 1c, and Fig. 3d). By 1200 UTC, most of observed storm cells had disappeared, while CLD predicts several storm cells in the cluster and a strong cell leading the entire storm cluster, which can not be matched with the observed cluster that had entered its dissipation stage.

When the cloud analysis is not used in NoCLD, the predicted storm cluster develops much slower than the fact and the forecast of CLD (Fig. 1b, c, and Fig. 3). By 0900 UTC, 3 hours forecast of NoCLD only triggers several small convective cells scattering at the southeast corner of Kansas and the conjoint point of Oklahoma, Arkansas, and Missouri. Three hours later until 6 hours forecast, the storm cluster begins to form in the experiment, while the observed storm cluster had been in its dissipation stage. At this time, the predicted cluster is also located behind the main part of the observed storm cluster and the one in CLD. Clearly, the forecast of the experiment NoCLD has severe spin-up problems in the formation of the storm cluster.

### 3.3. Individual Cells Captured by 5 Hours Forecast of CLD

It is found from the previous analysis that CLD can capture main characteristics of the storm cluster up to 6 hours. In this subsection, base-level reflectivity field of 5 hours forecast (valid at 1100 UTC) for experiment CLD and corresponding radar reflectivity observation are plotted in Fig. 4 to investigate the possible details of individual cell captured by the forecast. At 1100 UTC 23 May, the 5 hours forecast of CLD misses most of small cells observed by the radar, but the forecast does capture the location, strength, and shape of two observed main cells at this time (Fig. 4), one at the southeast front and one at the northwest end of the storm cluster. Interestingly, both predicted and observed southeast front cell of the storm cluster are elongated in the SW-NE direction, which may result from the strong downdraft at the decay stage of the storm cluster. The both predicted storm cells have a northward displacement error of about 50 km. Between the above two storms, CLD also gives a third storm that has no observed counterpart but has several relatively weak cells around it in the observation. Clearly, the 5 hour forecast of CLD correctly captures some details of the individual storms in the storm cluster.

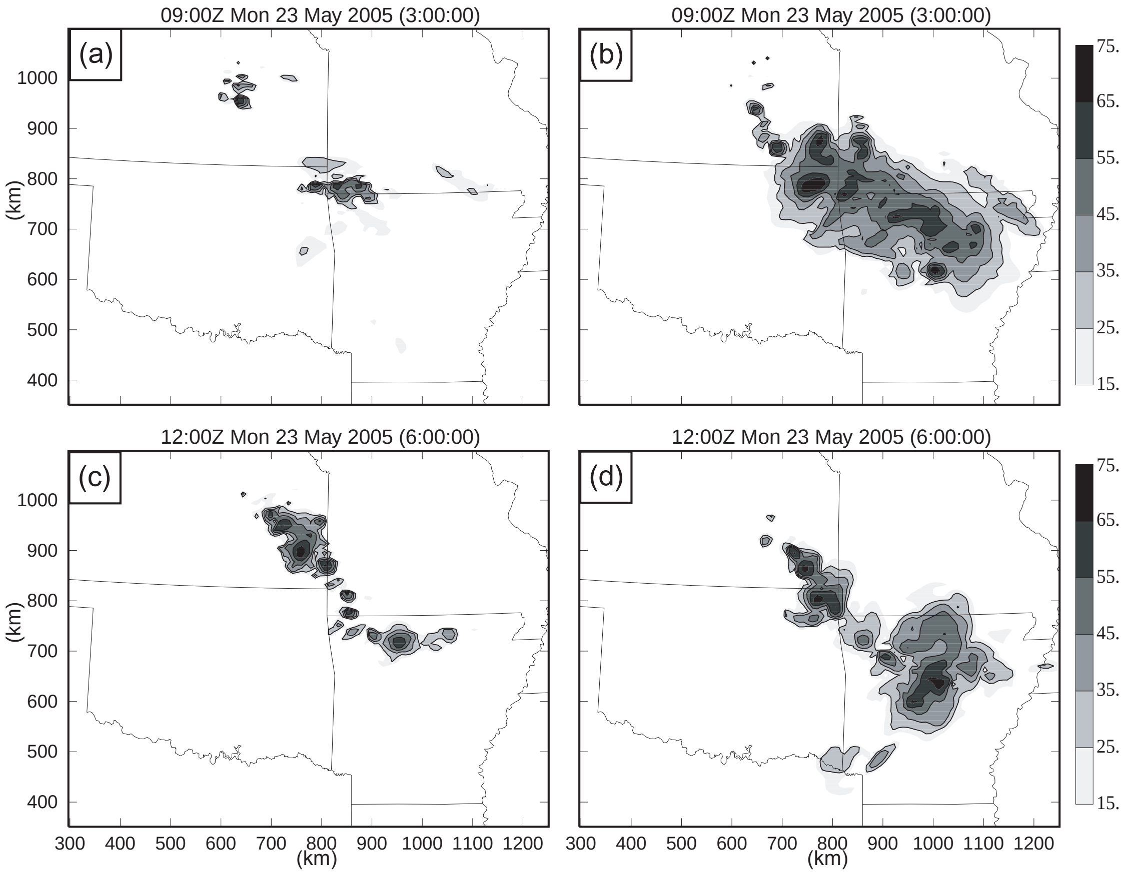


Fig. 3 Composite reflectivity fields of 3 and 6 hours forecast (valid at 0900 and 1200 UTC) from experiments CLD (right) and NoCLD (left). The domain shown is the same as Fig. 1

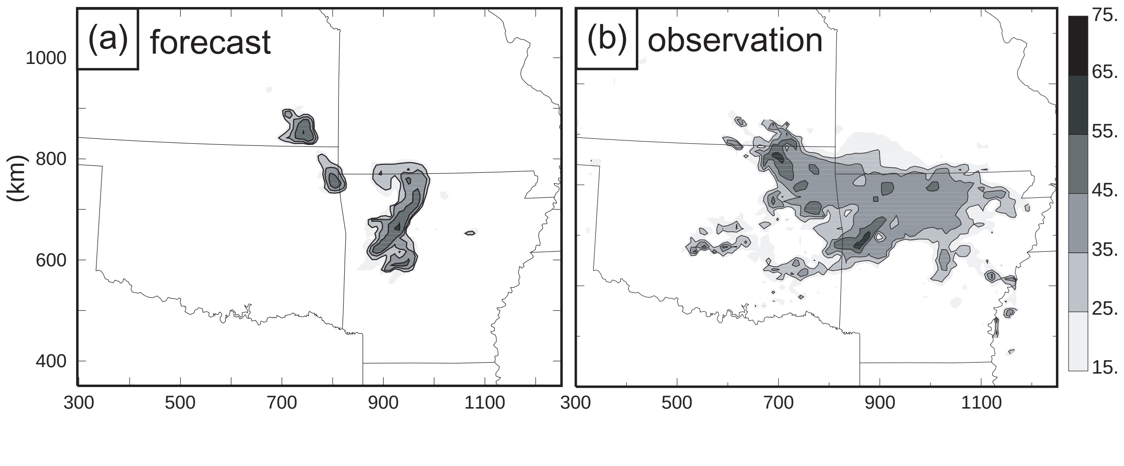


Fig. 4 Base level reflectivity field of 5 hours forecast (valid at 1100 UTC) for the experiment CLD (left) and corresponding radar reflectivity observation at the same level (right). The domain shown is the same as Fig. 1

## 4. Summary and Discussion

In this research, the ARPS cloud analysis procedure is successfully implemented in a proposed operational numerical simulation system, which includes the GSI analysis and the WRF-ARW model. It is found that the experiment using the cloud analysis with the reflectivity data can significantly improve the forecast for a storm cluster occurred in central plains on 23 May 2005.

In our previous study (Hu and Xue 2006; Hu et al. 2006), the ARPS cloud analysis procedure is used with the ARPS 3-Dimensional Variational (3DVAR) analysis and the ARPS model to simulate tornadic thunderstorms. Here, the proposed operational analysis system, GSI, is used to analyze conventional observations and provide background fields for the subsequent cloud analysis. Started from the initial fields in which the disturbances of the storm cluster in temperature, moisture, and hydrometer fields have been added through the cloud analysis, the proposed operational model, WRF-ARW, is used to run for 6 hours to simulate the evolution of the storm cluster from its mature stage to decay stage. It is found that the ARPS cloud analysis can work very well with the proposed operational forecast system and the subjective analysis of the experimental results indicates that using the cloud analysis can reduce the moisture spin-up problems and significantly improve the short-term (0-6 hours) forecast.

In our previous experiments, a 3-km horizontal grid spacing or even finer is used to simulate the evolutions of individual storm cells. In this study, a 9-km horizontal grid spacing is chosen as an example of possible operational grid resolution in the near future. The 9-km grid spacing falls in a gray area of choosing the parameterization or microphysics scheme for cloud and precipitation process in the model forecast. Although the ARPS cloud analysis is mainly designed and tuned for the storm-scale cloud system and the explicit radar reflectivity equations are used in the precipitation species retrievals, the study of this case shows that the ARPS cloud analysis can work well in the 9-km grid with the model that uses explicit microphysics scheme and improve the short-term forecast. This case also shows that 9-km grid forecasts can capture the main features of the storm cluster, which is relative large convective system, and miss most of the detailed evolution of the individual cells in the cluster. Therefore, we expect the cloud analysis can also improve the short-term forecast for other large convective systems like squall line and mesoscale convective complex (MCC).

The ARPS cloud analysis is mainly based on semi-empirical methods that run efficiently. To arrive at the best results of the analysis, many parameters in the analysis need to be carefully tuned according to the implement. In this study, the settings of the parameter are borrowed from our previous 3-km experiments for tornadic thunderstorms and they need to be carefully tested in the further study. Still, the positive impact of the cloud analysis on the forecast suggests it should be included in the proposed operational numerical prediction system.

In this study, the cloud analysis itself is done in the ARPS grid and the GSI analysis and WRF-ARW forecast are conducted in a different grid. The transition between the two computational grids makes the whole experiments very complex. Currently, we are working on incorporating the ARPS cloud analysis procedure into the GSI analysis system and conducted the cloud analysis directly in the GSI analysis space. This will make the implement of the cloud analysis much simpler and the assimilation of a time series of cloud observations possible.

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