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P9.8 A 3DVAR Application to Several Thunderstorm Cases Observed During VORTEX2 Field Operations and Potential for Real-Time Warning

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1. Introduction

As found by several studies (e.g., Burgess 1976; Burgess and Lemon 1991; Bunkers et al. 2006, 2009), the identification of a storm is supercell, or not is very important to accurate and timely severe weather warning operations. These studies revealed that 90% or greater of supercells are severe (i.e., tornadoes, large hails, strong wind damages). Therefore, proper early identification if a storm is a supercell, or a supercell imbedded in storm clusters would have been critical for early warnings of public for potential life saving, or property damage.

One of the important indications of a supercell is if a mesocyclone exists. Traditionally, *mesocyclone* is a radar term, defined as the Doppler radar velocity signature of a storm-scale (2–10-km diameter) vortex (Burgess, 1976), which corresponds to the rotating updraft–downdraft couplet of a supercell thunderstorm. It is cyclonic rotational and may contain the more intense tornado vortex. In last twenty years, several criteria have been established by several National Severe Storm Laboratory (NSSL) scientists (Burgess et al. 1976, 1982, 1991, 1993; Stumpf et al., 1998) for mesocyclone recognition based on a lot of Doppler radar observation, especially after the implementation of WSR-88D radars. Based on these criteria and other conceptual models (i. e., Lemon and Doswell 1979), the NSSL has developed a mesocyclone detection algorithm (MDA) that helps meet the needs of the meteorologists who has to make warning decisions (Stumpf et al., 1998). Though with great success, this method also failed to detect mesocylones sometimes. Some shortcomings exist. First, the method usually uses the data only from a single Doppler radar; it may easily overlook information contained in other nearby 88D Doppler radars. In other words, it does not take the full advantage of 88D radar network. Second, the method does not naturally combine other available information into the system, for example, NWP products and surface observations (In Oklahoma, Mesonet data are available).

The other hallmark characteristics of supercells, such as, the depth and persistence of the circulation, strength of updraft, and the maximum vertical vorticity magnitude are very difficult to identify in such a MDA method. Though the forecasters can make their warning decisions also based on all other available information, the timeliness requirement sometimes limits their ability to reach out to other available information. This has led to the call for an emphasis on the use of a fast data assimilation method as the optimal strategy to put all available information together as quickly as possible for the decision makers.

In this study, we investigate the possibility to identify supercells using a three-dimensional variational data assimilation method (Gao et al. 2004) developed for Advanced Regional Prediction System (ARPS, Xue et al. 2000, 2001, 2003) at the Center for Analysis and Prediction of Storms (ARPS 3DVAR). The system is used to do the analyses based on all available information including several nearby 88D radar data, NAM 12 km resolution NWP products, surface observations so that supercells can be quickly identified. This has potential to make best use of WSR-88D radar network and NWP products and helps meet the needs of the meteorologists who have to make warning decisions. The method is applied to several severe storms cases obtained during Vortex II field operations in summer of 2009. Our principal goal is to quantify the value of 3DVAR data assimilation system to real-time severe weather warning.

Section 2 provides an overview of the DA system and experiment design. Experiment results are assessed in section 3. We conclude in section 4 with a summary and outlook for future work.

2. The ARPS 3DVAR and Procedure Description

As introduced in the last section, the data assimilation method used in this study is a three-dimensional, variational DA system (Gao et al. 2002, 2003, 2004; Hu et al. 2006) that developed during the last several years. The ARPS 3DVAR system, designed especially for storm-scale data assimilation, uses a recursive filter (Purser et al. 2003a, b) with a mass continuity equation and other constraints that are incorporated into a cost function, yielding three-dimensional analyses of the wind components and other model variables. Multiple analysis passes are used that have different spatial in-

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fluence scales in order to accurately represent intermittent convective storms, while the quality control steps within the ARPS 3DVAR also are very important to improving the quality of the radial velocity and reflectivity data. There is also a cloud analysis system included within the ARPS 3DVAR which is not used here.

In the current study, we propose to develop a real-time weather-dependent hazard weather analysis and detection system on top of this 3DVAR method to best identify super cells using data from WSR-88D radar network and NWP product from NCEP NAM 12 km resolution analyses and forecasts. The procedures are as follows.

First, we start from getting a 2D Convective Outlook field of the National Weather Service (NWS) from previous day, and find the location (longitude, latitude) of maximum value of the Outlook. Then use this location as the center of the analysis domain, then select the necessary parameters for analysis domain, such as grid points, nx, ny, nz for three directions of space, and grid size dx, dy, dz. For our current settings, we choose nx=ny=400, dx=dy=1 km. Once the domain is chosen, we also need to get the terrain data. In the vertical, we use 31 terrain-following vertical layers, with nonlinear stretching, via a hyperbolic tangent function, and the average vertical grid size is 400 m. This step will be done very quickly. Hopefully, the domain is selected large enough with sufficient coverage to contain the principal features of interest while maintaining efficient computational advantage. For example, allowing the whole system run being finished within 4 - 9 minutes to keep its realtime value.

The second step is to get necessary background data, once the domain is selected. The NCEP operational NAM 12 km resolution analysis and forecast product is read in real-time settings and is interpolated into the grid we set up in the first step in both space and time using existing software developed within the ARPS model.

The third step is to figure out how many operational WSR-88D radars within the selected domain, get the necessary data in real-time, and perform quality control, thin and interpolate them into the analysis grid (this interpolation may be skipped in the future).

The fourth step is to do 3DVAR analysis using background field obtained from step two, and WSR-88D radar data obtained from step 3. Actually any available real-time data, such as, Oklahoma mesonet data (if the job runs within Oklahoma State) can be also used within this analysis.

The final step is post processing, including identifying the position of supercells, maximum vortices, maximum vertical velocities, and producing some products that can be easily understood by the forecasters who issue severe weather warnings.

The above 5-step procedure can be performed every 5, or 10 minutes depending on computational cost and users' needs. By carefully design domain size, vertical levels, based on computer resources, we hope that the overall calculation can be finished within 5 minutes. By integrating many datasets together from different sources using the data assimilation method in real-time may ensure that the forecasters have enough time to direct their attention towards improving severe weather forecasts and increase the leading time on warning the public of the potential threat by looking at less datasets.

By using all available information simultaneously, it is possible to determine the 3-D winds and other variables as accurate as possible, and the quality of reflectivity data coverage also can be greatly improved through 88D radar network. Currently, we only focus on 3D wind analysis and wind derived variables such as, vertical velocities and vortices.

3. Some Preliminary Results

To make sure the 3DVAR analysis produce reasonable results, we first apply the 3DVAR program to several supercell cases observed during the 2009 Vortex II field experiments. We follow the procedure described in the last section except the first step because these events already happened.

The first case is a tornadic supercell event that took place on June 05, 2009 in Goshen County, Wyoming. The tornado was graded as EF-2. It touched down near 2207 UTC, and lasted about 13 minutes. The supercell related to this tornado lasted for over 2 hours. The Vortex II project scientists well documented this event from the beginning to the end. But we will only use three nearby WSR-88D radars to do our analysis. For this case, radar data from three radars at Cheyenne, WY (KCYC), Denver, CO (KFTG), Rapid City SD (KUDX) are used in the 3DVAR analysis program.

The evolution of the supercell storm as indicated by the analyzed radar reflectivity, horizontal winds, and vertical vorticity at the 3 km level is shown in Fig. 1 from 21:00 to 22:40 UTC. The wind analysis at this level indicates a very strong mid-level cyclonic circulation started from 2120UTC and lasted until the end of the analysis. The mesocyclone first developed near the middle level and gradually reached the ground at 21:20 UTC and maintained pretty strong and deep until 22:20 UTC. The development of WER feature (though not very classic) within the supercell core was evident around 21:20 UTC, and much more clear at 22:00 UTC when the tornado touched down (Fig 2). This storm moved gradually to the east direction. During this period,

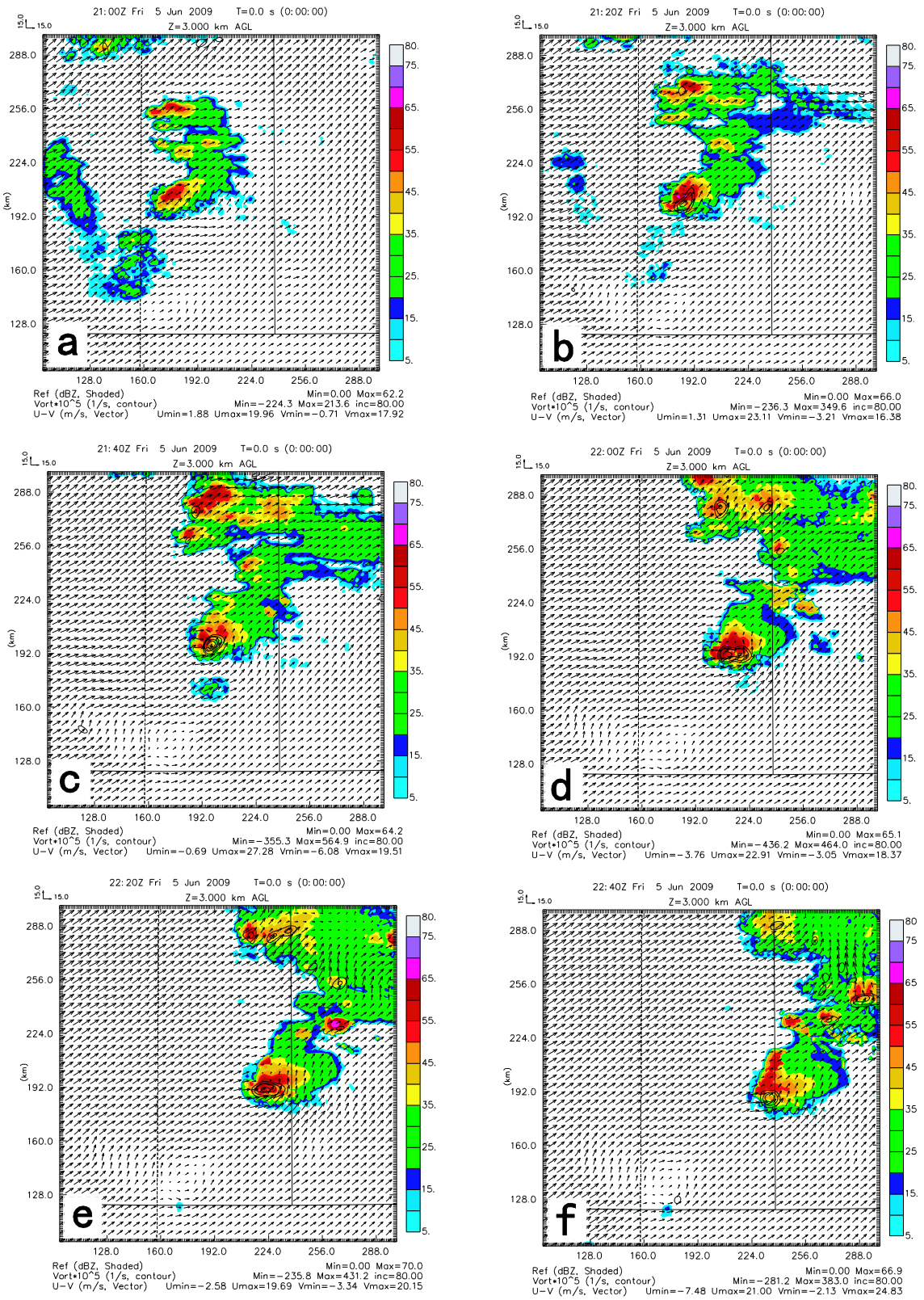

Fig. 1. The analyzed reflectivity, horizontal wind fields, and vorticity at z=3 km using data from KCYS, KUDX, and KFTG radars valid at (a) 2100 UTC, (b) 2120 UTC, (c) 2140 UTC, (d) 2100 UTC, (e) 2220 UTC, and (f) 2240 UTC, June, 05 2009 near Goshen, WY.

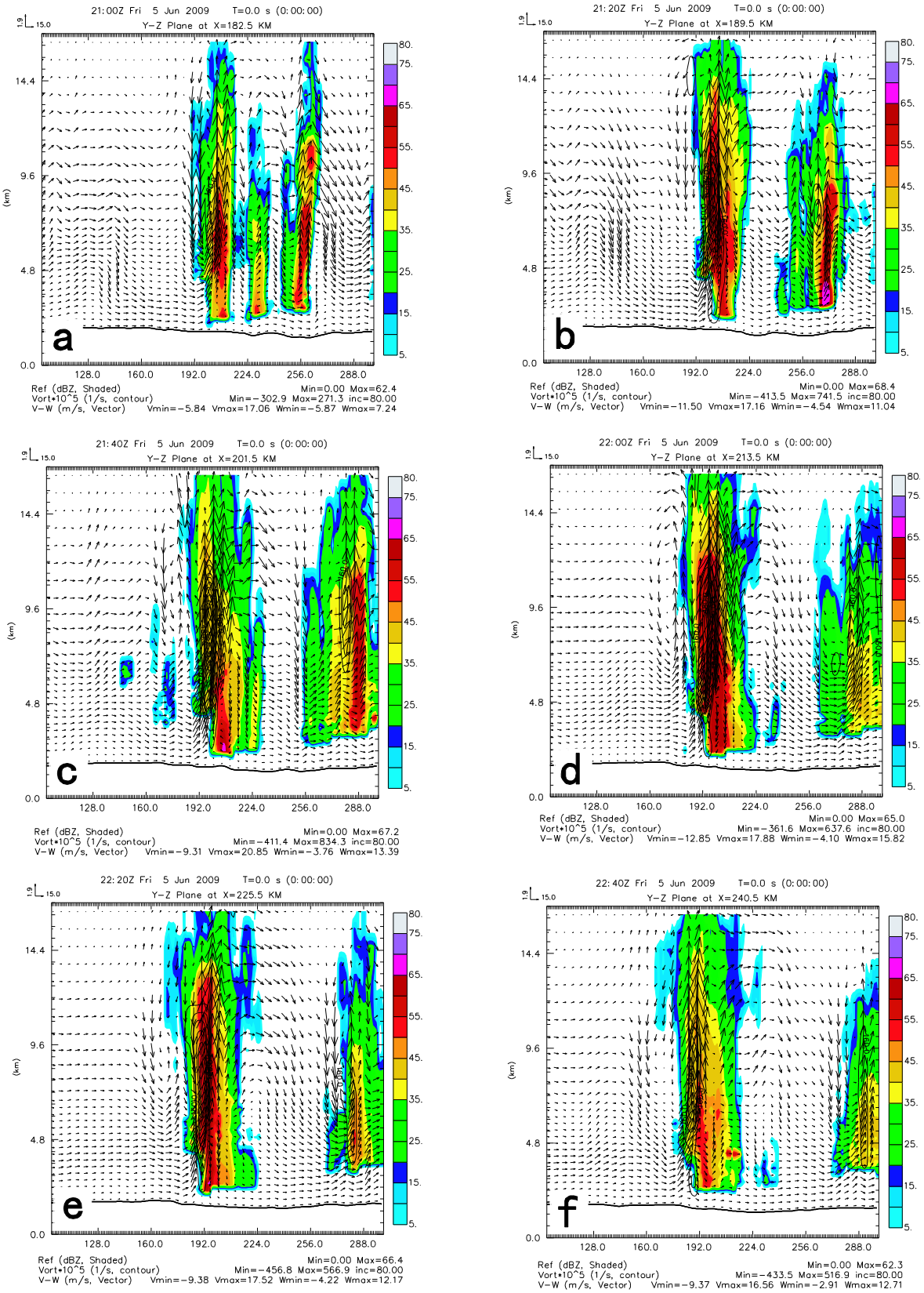

Fig. 2. Same as Fig. 1, but for vertical slice through the maximum vertical velocity.

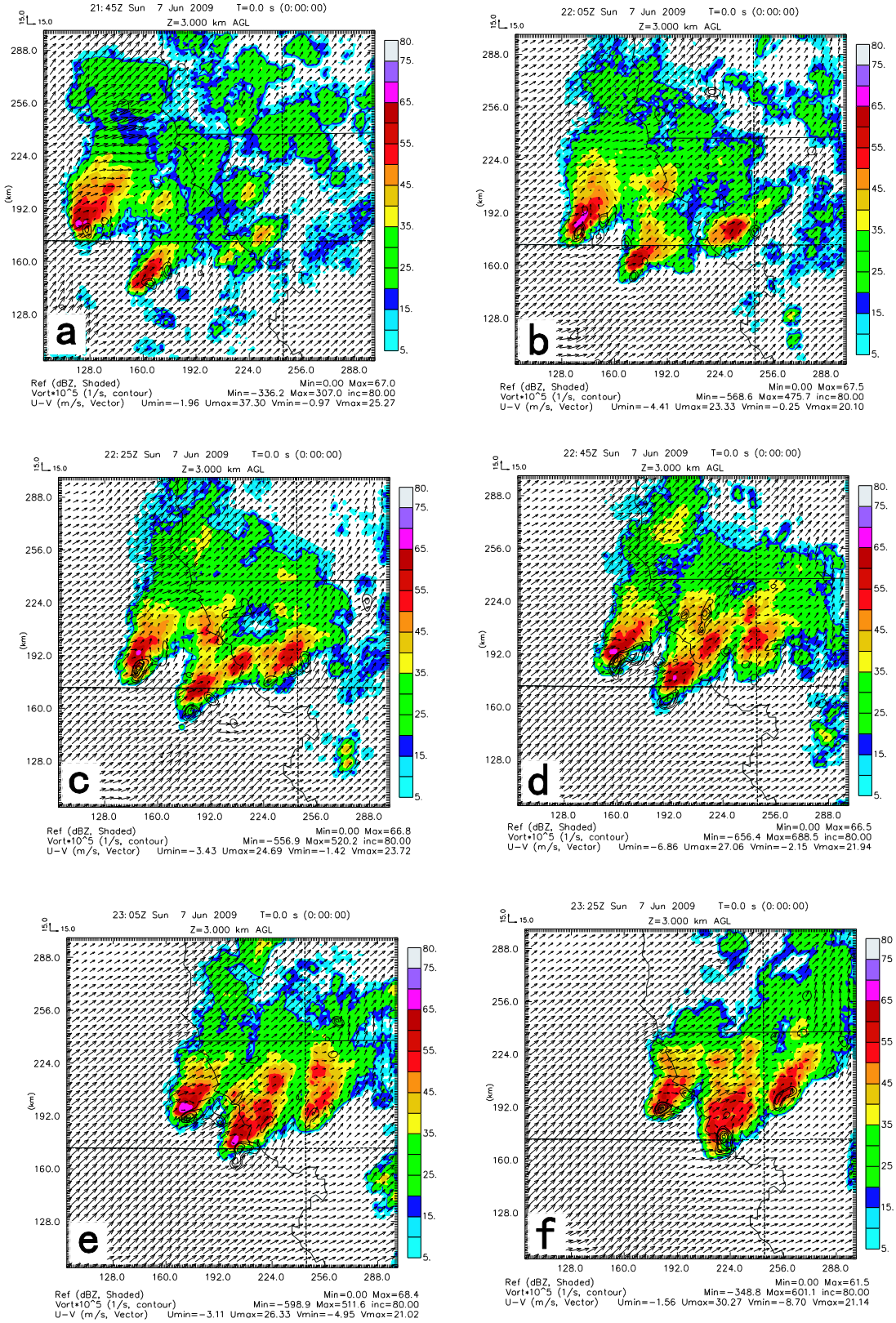

Fig. 3. The analyzed reflectivity, horizontal wind fields, and vortices at z=3 km using data from KTWX, KEAX, KOAX and KDMX radars valid at (a) 2145 UTC, (b) 2205 UTC, (c) 2225 UTC, (d) 2245 UTC, (e) 2305 UTC, and (f) 2325 UTC, June, 07 2009 near the joint boundary of three states NE, KS, MO.

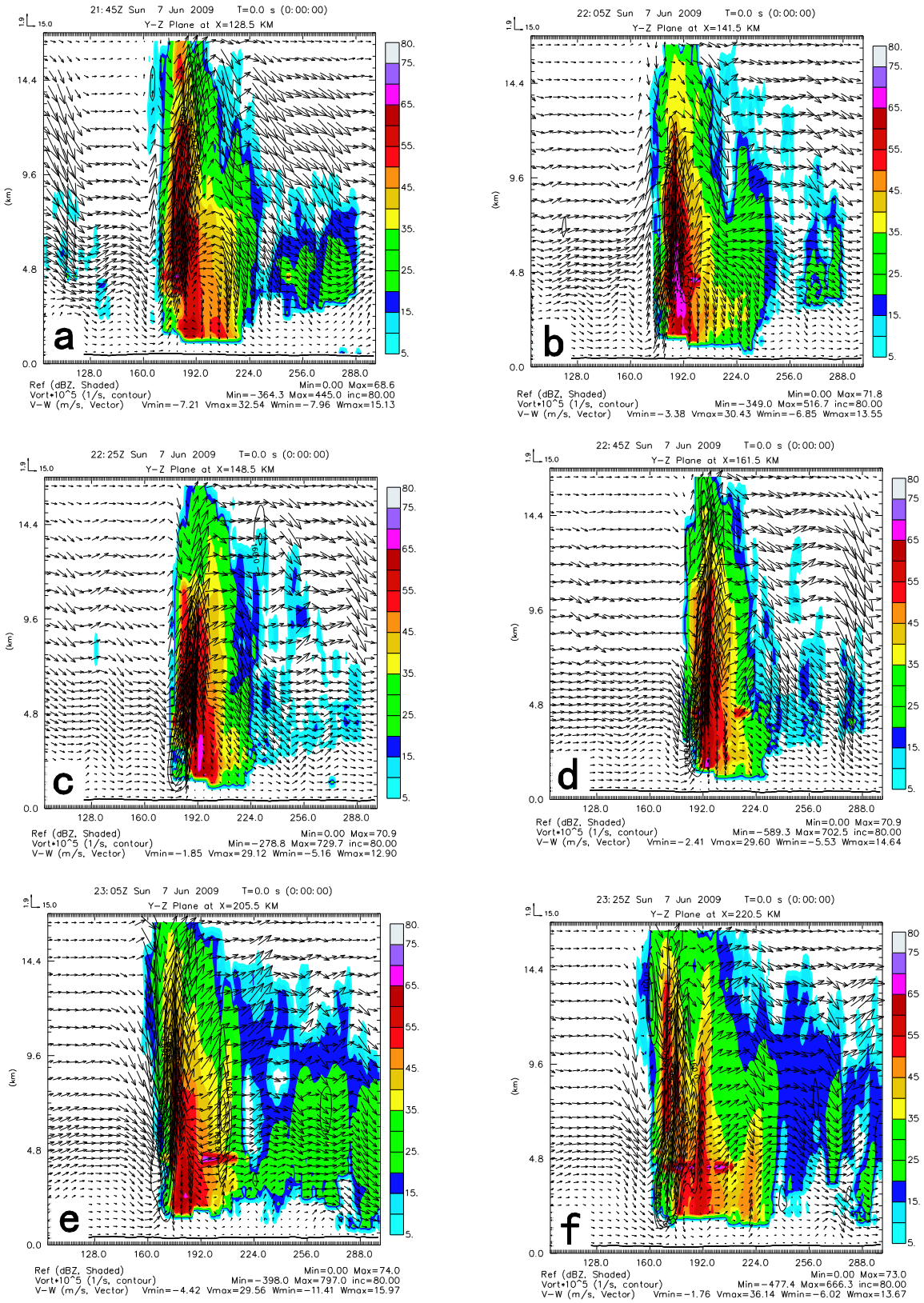

Fig. 4. Same as Fig.3, but for vertical slice through the maximum of vertical velocity.

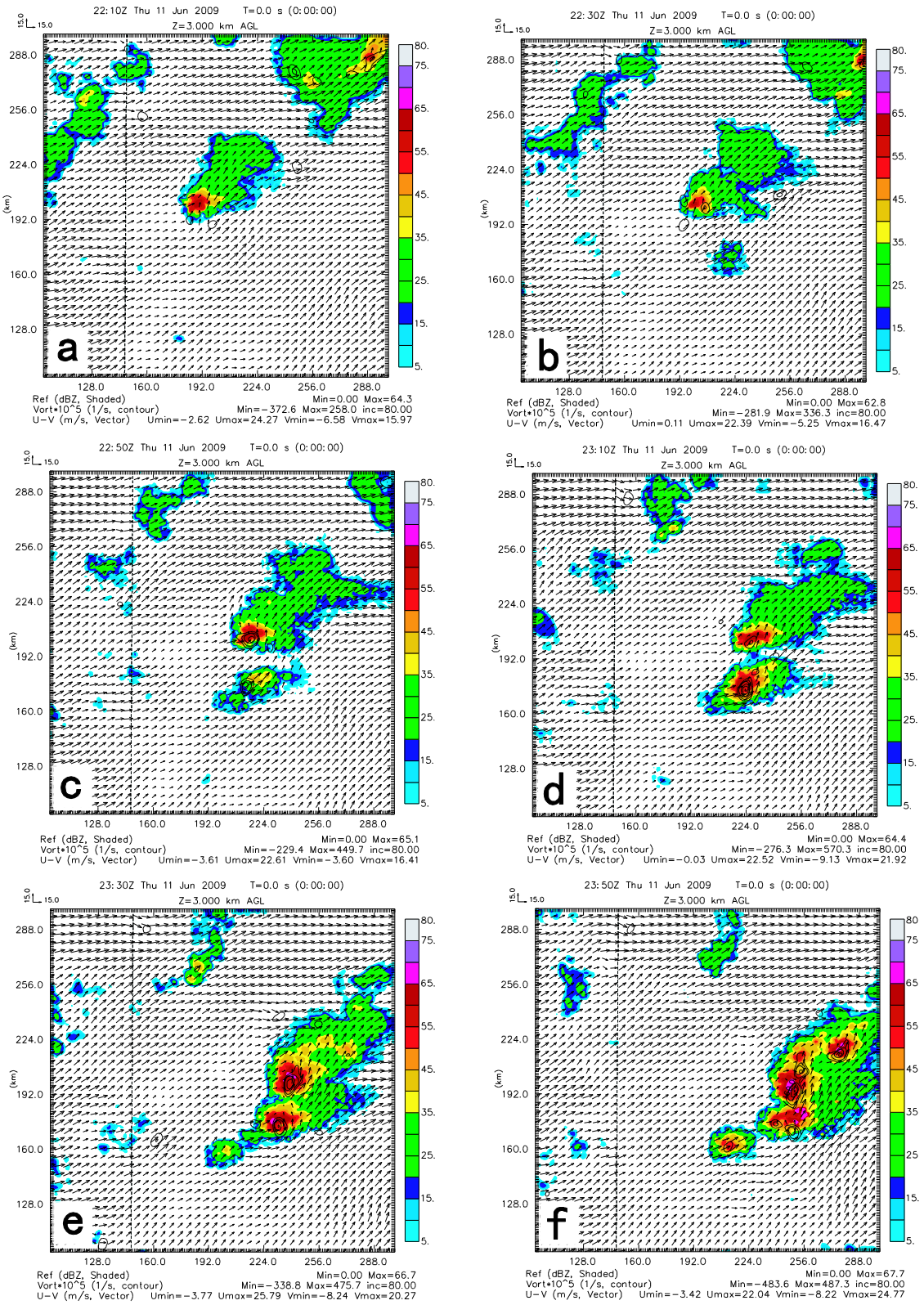

Fig.5.The analyzed reflectivity, horizontal wind fields, and vortices at z=3 km using data from KPUX, and KFTG radars valid at (a) 2210 UTC, (b) 2230 UTC, (c) 2250 UTC, (d) 2310 UTC, (e) 2330 UTC, and (f) 2350 UTC, June, 11 2009 near PUEBLO, CO.

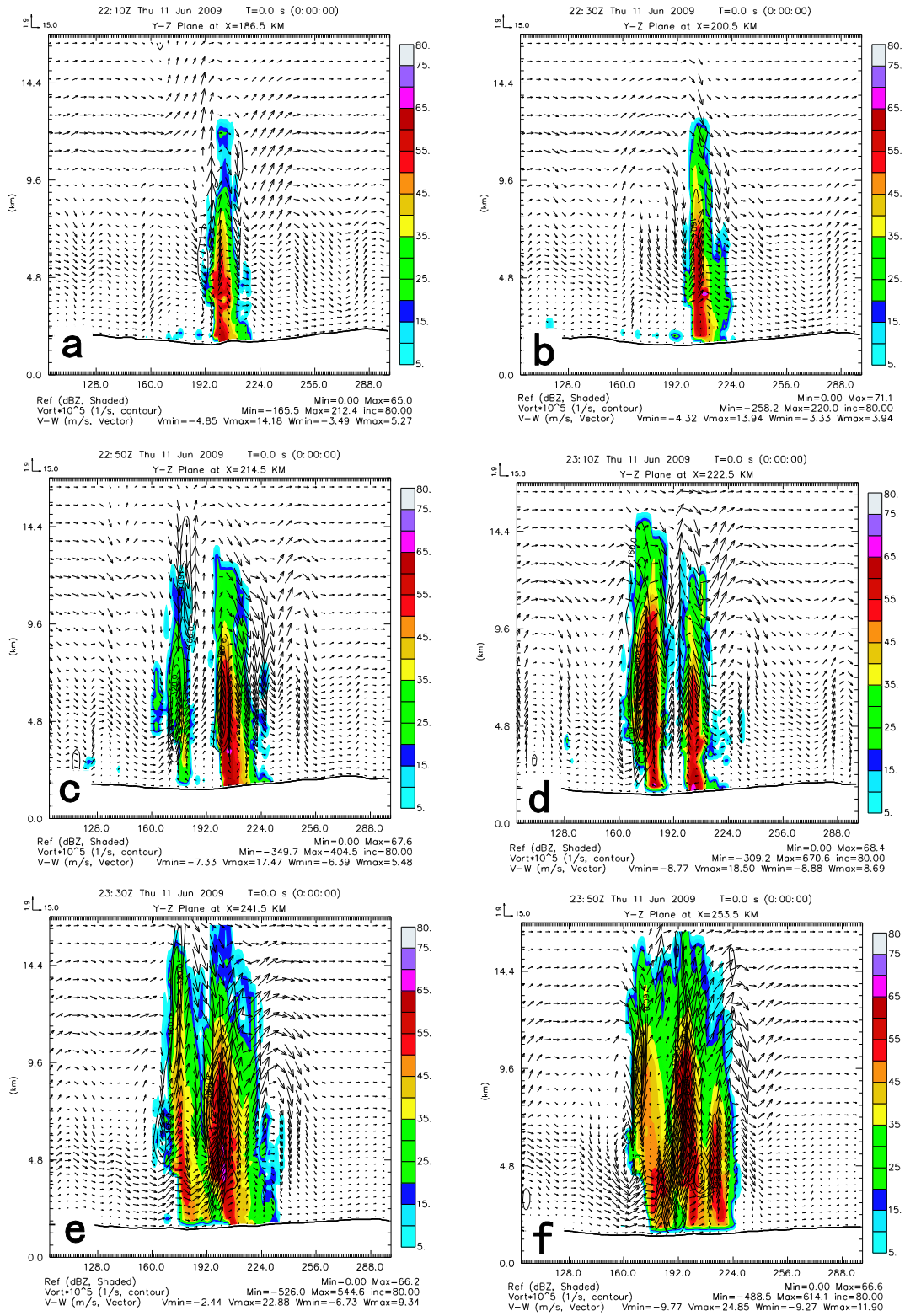

Fig. 6. Same as Fig.5, but for vertical slice through the maximum of vertical velocity.

the storm produced large hails and a EF-2 hit the ground around 22:07 UTC in Gaoshen County. The supercell became weak after passing the boundary of two states Wyoming and Nebraska (Fig 1f and 2f).

The second case is a nontornadic supercell event that took place in Bates, and Mound County, MO (Fig 3, 4). For this case, the reflectivity and radial velocity from nearby four radars at Topeka, KS (KTWX), Kansus City, MO (KEAX), Omaha, NE (KOAX), Des Moines, IA (KDMX) are used in the 3DVAR analysis system. The storm environment was very suitable for severe weather developments during that day. Many large hails and several tornadoes were reported across western great plain. There are several storm cells developed in southeast of Nebraska, propagated to the joint boundary of three states NE, KS, MO from 21:30 UTC, 7 June to00:00 UTC, 8 June. At least two cells among them developed into supercells (Figs. 3, and 4). During the process, the left (or the west) cell first became supercell. The hook echo appeared at 21:45 UTC and maximum vertical velocity reached above 15 ms^{-1} (Fig 3a, 4a). The WER was also evident near the area of maximum updraft below 4 km level, and vertical vortices was weak below 4 km level, but above 4 km, the maximum vorticity was above 0.004 s^{-1} for this 1 km resolution analysis (Fig 4a). After this time, the rotation gradually reached to the ground and maintained pretty strong until 23:25 UTC (Fig. 4c, d, e, f). Both supercell storms were well organized and the development of rear flank downdraft (RFD) were also very clear at several time levels (Fig 4c, d, e, f), and during this time period, golf ball size hail observed from the viewer of a TV station.

The third case is another nontornadic supercell event that took place in Larimer county, CO (Fig 5, 6). For this case, only two radars are used. One is at Denver, CO (KFTG), and another is Pueblo, CO (KPUX). In this case, there were still two major supercells, but developed in different stage. Comparing with two previous cases, the primary storm updraft cores were not so deep and the maximum vertical velocity are less than 10 ms^{-1} most of time, but the intensity of circulation are almost same as two previous cases. The first cell (or North cell) developed around 22:10 with very weak updraft (only 5.27 ms^{-1}, Fig. 6a). This storm cell moved slowly to the east and maintained its strength throughout the entire one and half hours analysis period. Another cell (or south cell) initialized at 22:30 UTC and became a well organized supercell around 23:10 UTC. The circulations for both supercells became the strongest around 23:30 UTC and large hails were reported before and around this time level. Though no tornado reported for this case, and the vertical velocities were weaker, these two cells were still supercell storms. The atmosphere was quite instable around 23:50 UTC, new cells developed at both southwest and northeast of these two supercells (Fig 6f).

Our analyses for all three cases indicate there are no distinguishable differences among tornadic and non tornadic supercells. This is no surprise because the resolution of our analyses is only 1 km in horizontal, and this resolution may be beyond the resolvable scale of telling tornadic supercells from those nontonadic ones. Though much higher resolution analyses can be performed, the radar data we used is also about same resolution. The other high resolution data may be needed to identify the difference between tornadic and nontornadic supercells.

5. Summary

Radar is a fundamental tool for severe storms monitoring and nowcasting activities. Forecasters can interpret radar images directly and issue severe storm warning based on their judgment. However, there are many situations that even the well trainer forecasters cannot make a sounding judgment based on information from only single 88D radar images. To take advantages of WSR-88D radar network and recently easy-accessed high resolution NWP products, and help forecasters to provide precise and timely weather warnings of convective phenomena, we proposed a data assimilation based supercell analysis and detection procedure to mix possible all available information together. The proposed method may have potential to provide a mechanism to locate severe weather threat with possible more accuracy than the current NSSL MDA method. The objectivity of the procedure ensures that (i) using all available information, including nearby several 88D radars and NAM high resolution NWP products, (ii) may help forecasters to make their decisions in a timely manner, and (iii) the problem of subjectivity, inherent to some arbitrary criteria (for example implemented in NSSL MDA), is avoided. Furthermore, the method can be run automatically and enables, for example, the study of a specific area in greater detail or the investigation of the evolution and lifetime of certain kinds of severe weather.

The method is capable of detecting and following the evolution of supercells based on several case studies. This is probably the first step to use this method to nowcast the severe weather events, such as tornadoes, large hails and strong damage winds. The NSSL MDA is very useful for studying severe weather events for skillful forecasters. To use it requires knowledge of Doppler radar and pattern recognition skills. But 3DVAR may provide more intuitional products that can be easily understood by any forecasters. Also, the output of our 3DVAR analysis can be injected into NSSL

MDA system to form a more reliable severe weather detection system. This will be our future work.

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