115 Extended Abstract, 35th Conf. on Radar Meteorology
Amer. Meteor. Soc., Pittsburgh, PA, September 26-30, 2011

The Application of A Realtime Weather-Adaptive 3DVAR Analysis System for Severe Weather Detections and Warnings with Automatic Storm Positioning Capability

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1. Introduction

The proper early identification of a supercell thunderstorm, or a supercell imbedded in a cluster of storms, is critical to the issuance of public warnings for severe weather. Several studies by Burgess (1976), Burgess and Lemon (1991), and Bunkers et al. 2006, 2009) found the determination of whether or not a thunderstorm is a supercell thunderstorm is very important to accurate and timely severe weather warning operations. These studies revealed that over 90% of supercells are severe (i.e., produce tornadoes, large hail, or severe surface winds).

One of the most important indicators of a supercell is the existence of a mid-level mesocyclone. The mesocyclone is originally 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. Mesocyclones in the United States are often cyclonic and may also contain the more intense tornado vortex. In last twenty years, several criteria have been established for mesocyclone recognition based on a wealth of Doppler radar observations, especially after the implementation of WSR-88Ds (Burgess et al. 1976, 1982, 1991, 1993; Stumpf et al., 1998). Based on these criteria and other conceptual models (i. e., Lemon and Doswell 1979), a mesocyclone detection algorithm (MDA) was developed that helps meet the needs of the meteorologists who have to make warning decisions (Stumpf et al., 1998). Although this approach has met with great success, some shortcomings exist. Most importantly, the method uses the data from only Doppler radars; it does not incorporate information from NWP models and other available observations. In other words, it does not take the full advantage of information available to communities.

The other hallmark characteristics of supercells, such as the depth and persistence of the circulation, the strength of updraft, and the maximum vertical vorticity magnitude, are very difficult to identify with the MDA method based upon radar observations alone. While forecasters make their warning decisions based on all available information, the escalating data flow rates from new sensors and applications will make it challenging for forecasters to make the best use of all the available data in warning operations. The workload and timeliness requirement may limit their ability to effectively use all available information. This situation has led to the call for an exploration of the use of fast data assimilation methods as potential solutions for merging all available information together as quickly as possible for the human decision makers.

In this study, we investigate the possibility of merging all available information together and identifying mesocyclones by using ARPS 3DVAR system, which is a three-dimensional variational data assimilation method (Gao et al. 2004) developed for Advanced Regional Prediction System (ARPS, Xue et al. 2000, 2001). The system is used to produce physically-consistent high-resolution analyses based on the data sources including observations from several nearby WSR-88Ds, operational North American Mesoscale (NAM) model 12 km grid spacing analysis and forecast products, and surface observations. The analysis system may have potential to make better use of observations from the WSR-88D network, along with operational model forecast products, and thereby can help to meet the needs of the meteorologists who have to make warning decisions. Although still in the early development stage, the system performed very well during the spring of 2010. Many severe weather events were all successfully detected and analyzed. Our principal goal is to evaluate the potential value of 3DVAR data assimilation system for real-time severe weather warning.

Section 2 provides an overview of the data assimilation (DA) system and the 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. 1999, 2002, 2004; Hu et al. 2006) which has been developed during the last ten

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years. The ARPS 3DVAR system, designed especially for storm-scale data assimilation, uses a recursive filter (Purser et al. 2003) with a mass continuity equation and other constraints that are incorporated into a cost function, yielding physically-consistent three-dimensional analyses of the wind components and other model variables. Multiple analysis passes are used that have different spatial influence 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. A real-time weather-dependent hazardous weather analysis and detection system based upon this 3DVAR method is developed to identify supercells and other severe weather events using data mainly from the WSR-88D network and from the NCEP NAM 12 km resolution analyses and forecasts. The steps needed to make such a system operationally in real time are as follows.

First, we obtain the two-dimensional composite reflectivity product from the National Severe Storm Laboratory (NSSL) Warning Decision Support System - Integrated Information (WDSS-II) group, and use it to identify a potential location (longitude, latitude) at greatest risk for severe storms. This is done every 30 minutes. The identified location is used as the centers for the 3DVAR analysis domain. Parameters are then selected for the analysis domain, including the number of grid points, nx, ny, and nz in the three spatial directions and the grid spacings dx, dy, and dz. For the current study, we choose nx=ny=200, dx=dy=1 km. In the vertical, we use 31 terrain-following vertical layers, with nonlinear stretching, via a hyperbolic tangent function, yielding an average vertical grid spacing of 400 m. Once the domain is defined, the terrain data are interpolated to the analysis grids. The challenge here is to select a domain that is large enough to contain the principal features of meteorological interest while maintaining an efficient computational advantage so that the analyses can be produced fast enough to be of use in operations. Currently, the domain size is only 200kmX200km. This will be enlarged in the future when the computational power is increased.

Once the analysis domain is selected, the second step is to get the necessary background data. The NCEP operational NAM 12 km resolution analysis and forecast product is obtained and interpolated to the analysis domain in both space and time using existing software developed within the ARPS model. While the spatial interpolation is determined by the grid spacing of the 3DVAR analysis, the frequency of the time interpolation is determined by how often the end users wants analyses to be produced. Currently, the analyses are produced every five minutes, which corresponds closely to the 4-6 minute period required for the WSR-88D to complete a full volume scan.

The third step is to determine how many operational WSR-88Ds are present within the selected domain. To make sure the maximum data coverage, a big domain 400kmX400km is used within which the available WSR-88D data are obtained in real-time. Then, a necessary quality control is performed on these radar observations. After this, the thinning, and interpolation of the radar data onto the analysis grids are performed.

The fourth step is to conduct the 3DVAR analysis using both the background field obtained from step two, and the WSR-88D data obtained from step 3. Any additional available real-time data, such as mesonet data can be also used within this analysis with little additional computational cost.

The final step is the post processing of the resulting analyses, including identifying the position of supercells, obtaining two-dimensional composite vorticity tracks and two dimensional vertical velocity tracks from analysis, and producing other products that can be effectively used by the forecasters who issue severe weather warnings.

The above 5-step procedure is performed every 5 minutes or longer depending on computational cost and users' needs. Currently, by carefully choosing the domain size and number of vertical levels, in relation to our available computer named Landru with 128 processors and Message Passing Interface supported computational capacity), each analysis can be finished within 5 minutes or less. By using all available information simultaneously, it is possible to determine the 3D winds and other variables as accurately as possible, while also improving the quality of reflectivity data coverage. As initial application, in the analyses that follow, we only focus on the 3D wind analyses and wind-derived variables, such as vertical velocity and vorticity.

3. Some Preliminary Results

To assess the potential of the 3DVAR analysis to assist in warning operations, the above system was implemented in 2010 spring experiments for testing purpose. We present here the performance of the system by examining three example supercell cases observed during the 2010 spring experiments. We follow the procedure described in the last section. The analysis domain is floated based on WDSS-II 2D composite reflectivity product.

The first case is a tornadic supercell event that took place on 25 May 2010 near Tribune, Kansas. Two supercells developed over 3 hours period and over dozen tornadoes touched down during that period (Fig 1a). The VORTEX2 project scientists observed this event partially and recorded some valuable dataset. We use radial velocity and reflectivity observations from several nearby WSR-88Ds KGLD, KUEX, KVNX and KDDC in the 3DVAR analysis (Fig. 1b).

In the realtime analysis, the 200km x 200km domain is relocated and floated every half hour. In the first example, the evolution of two supercell storms during half hour, from 0100 UTC – 0130 UTC May 26, as indicated by the analyzed radar reflectivity, horizontal winds, and vertical vorticity at the 3 km above ground level is our focus and is shown in Fig. 2. During this half hour period, a strong hook echo for the right-moving cell in the reflectivity field is very clear even at this 3km level. The wind analysis at this level indicates a very strong mid-level cyclonic circulation (black contours) persist and is co-located with reflectivity hook echo until the end of the analysis. This cell, along with the left and weaker storm cell, moves slowly from west to east to the center of the analysis domain. The mesocyclone maintains its strength (close to 0.001 s^{-1}) and vertical extent about 10 km deep (not shown) through the half hour analysis period. During this period, the storm produces large hail and the tornadoes reach the ground around 0106 UTC, 0114 UTC and 0128 UTC in Tribune, Kansas according to SPC reports (Fig 1a).

The second case examined is a tornadic supercell event that took place in between Colorado and Oklahoma Border (Figs. 3a). For this case, reflectivity and radial velocity observations from three nearby WSR-88Ds, KPUX, KGLD, and KDDC are used in the 3DVAR analysis system (Fig 3b). The storm environment looks not suitable for severe weather on this day, but one supercell developed and produced tornadoes anyway. For this case, all the three 88D radars are far away from the storm center, but still storm structures at middle and up levels are well analyzed (Fig 4). At 3km above ground, a strong mesoclycone is found and maximum vorticity maintain above 0.008 ms^{-1} at several time levels (Fig 4a, b, c, e and f). During this time period (0100 UTC – 0125 UTC, June 1), several tornadoes were observed near Campo, Colorado and lasted for at least 20 minutes (Fig. 3a). This is a good example that the mesocyclone that associated with tornado outbreaks can still be detected even if the WSR-88D radars are far from the storms.

The third case is another tornadic supercell event that took place in Denver, Colorado (Fig 5a). For this case, observations from four WSR-88D radars KFTG, KCYS, KGLD and KPUX are used, and KFTG from Denver closely observed two supercells storms that produced tornadoes (Fig. 5a, b). In the analysis, two major supercells also move slowly from west to east during our half analysis period from 0100 UTC to 0125 UTC, June 11. The right-moving storm first produces one tornado, then becomes weaker while propagating to the east. The left and southern storm becomes stronger and produces three tornadoes along the way during the half hour (Fig. 5a, 6). Comparing with the two previous cases, the primary storm updraft core are very deep and are extended vertically about 10 km, and the maximum vertical velocity is greater than 20 ms^{-1} most of time. The WER is also evident near the area of maximum updraft below 4 km level (Fig. 7a, b, d, f).

4. Summary

Radar is a fundamental tool for severe storm monitoring and nowcasting activities. Forecasters examine real-time WSR-88D observations, radar algorithm products, and use their considerable experience and situational awareness to issue severe storm warnings that help protect the public from hazardous weather events. However, there are situations for which even well-trained forecasters find it challenging to make a quick and sound judgment based on information from many sources. To take more complete advantage of the full information content from the WSR-88D network and recently easy-to-access high resolution NCEP operational model analysis and forecast products, we developed a weather-adaptive analysis procedure which can be used for severe weather detections, especially detection of mesocyclones at middle atmospheric levels from 3-5 kilometers. The method used is 3DVAR method developed for ARPS model. The proposed method may have the potential to provide improved information for making severe weather warning decisions. The objectivity of the procedure ensures that (i) all available information, including nearby several WSR-88Ds and NAM high resolution analysis and forecast products, are used, (ii) physically-consistent gridded data are provided to forecasters to help make their decisions in a timely manner, and (iii) the problem of subjectivity, inherent to some arbitrary criteria (for example implemented in the MDA), is avoided. Furthermore, the analysis method can be run both automatically offline. This 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 potential of this method has been demonstrated by detecting the initiation and evolution of supercells from many real data cases. This study represents the first step in the assessment of this type of analysis approach for use in severe weather warnings, such as tornadoes, large hail and strong damaging winds. While we recognize that the MDA is very useful for identifying supercell thunderstorms, analyses from a 3DVAR approach may provide more intuitive products that can be just as effectively used by forecasters, while also providing the benefits gained from using observations from multiple WSR-88Ds and other data sources. Alternatively, the output of a 3DVAR analysis can be inserted into MDA-like algorithm for use in warning operations. This will be our future work.

Acknowledgments. This research was primarily funded by the National Severe Storm Laboratory Warning and Forecast project. The first author was partially supported by NSF grants ATM-0738370. We'd like thanks Scott R. Dembek and Jack Kain for their help with NSSL computer Landru usage. The assistance of NSSL IT team, Brett Morrow and Steve Fletcher are gratefully acknowledged.

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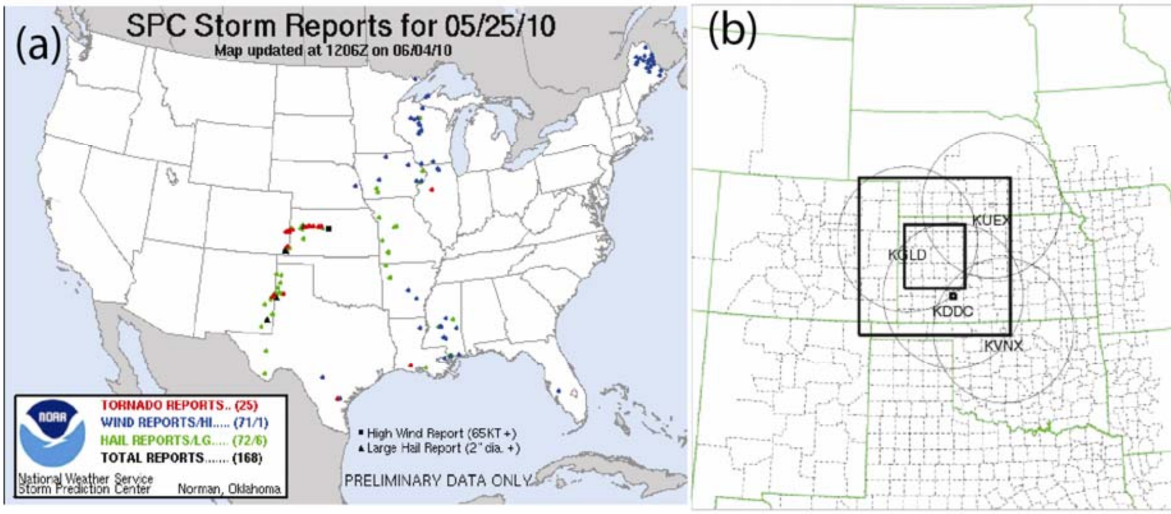

Fig. 1. May 26, 2010 Kansas tornadic storm event. (a) The storm report from Storm Prediction Center (SPC); and (b) the illustration of 3DVAR analysis domain. The inner domain of 200x200 km is used for 3DVAR analysis. The outer domain of 400x400 km is used to identify 88D radars to be used.

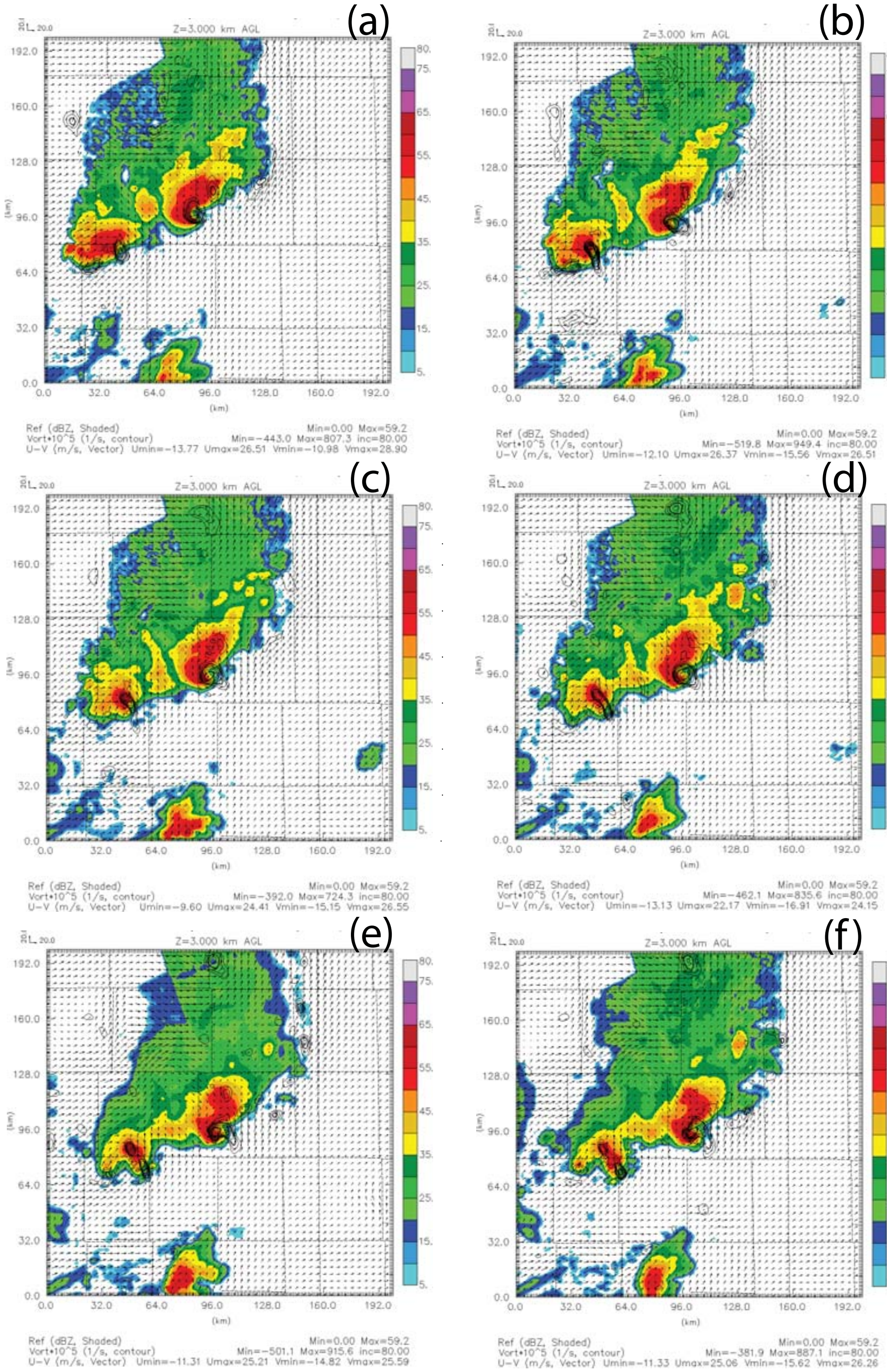

Fig. 2. The analyzed reflectivity, horizontal wind fields, and vorticity at z=3 km using data from KGLD, KUEX, KDDC, and KVNX radars valid at (a) 0100 UTC, (b) 0105 UTC, (c) 0110 UTC, (d) 0115 UTC, (e) 0120 UTC, and (f) 0125 UTC, May 26, 2010 near Tribune, KS.

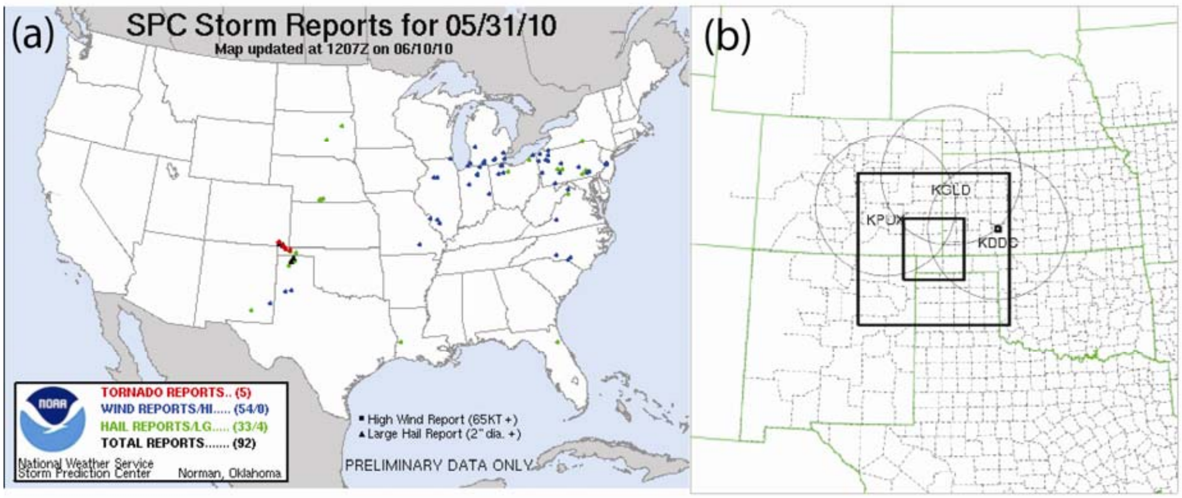

Fig. 3. Same as Fig. 1, but for Campo Colorado tornadic storm event May 31, 2010.

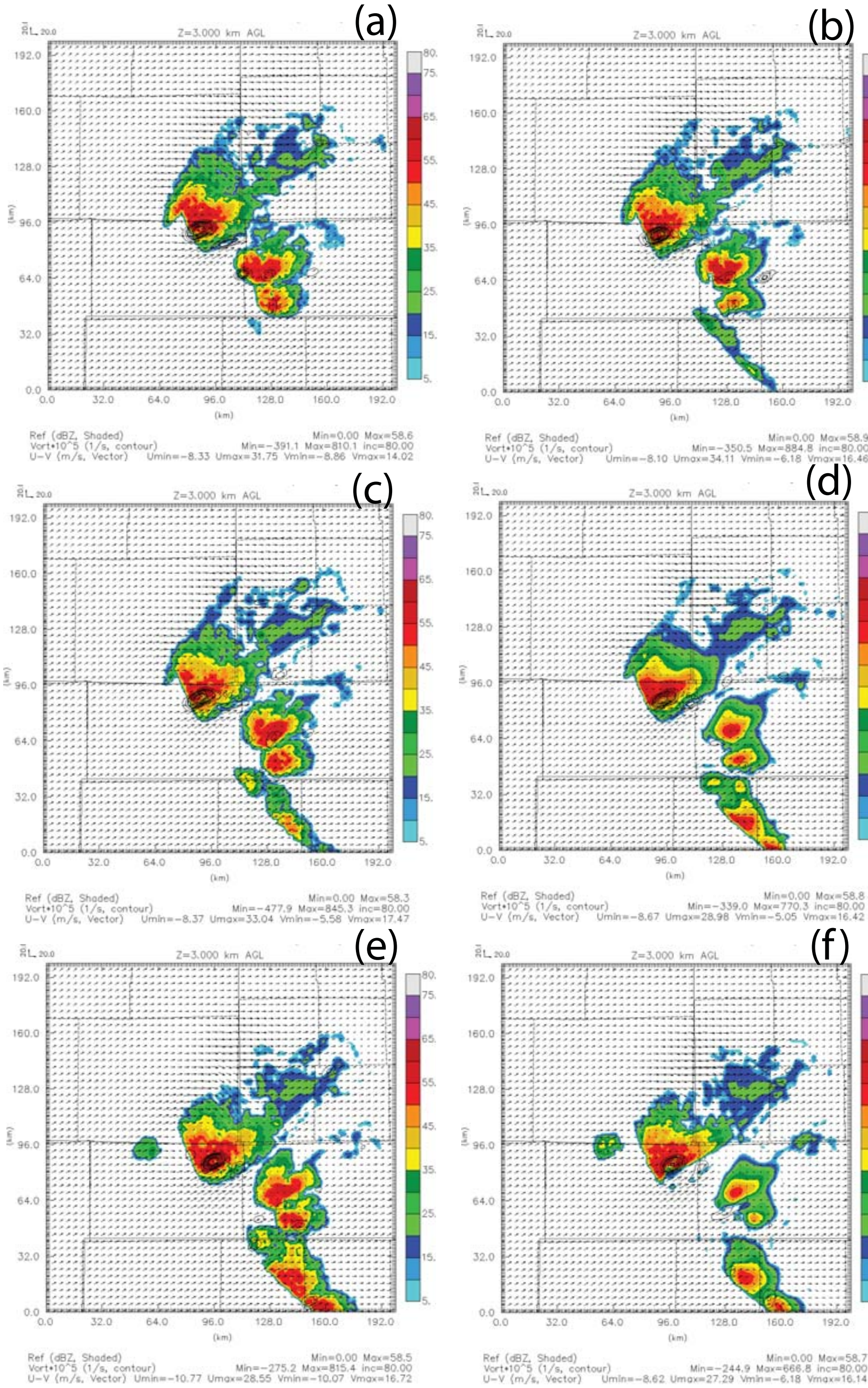

Fig. 4. The analyzed reflectivity, horizontal wind fields, and vortices at z=3 km using data from KPUX, KGLD, and KDDC radars valid at (a) 0100 UTC, (b) 0105 UTC, (c) 0110 UTC, (d) 01115 UTC, (e) 0120 UTC, and (f) 0125 UTC, June, 01 2010 near Campo, Colorado (Near the border of Colorado).

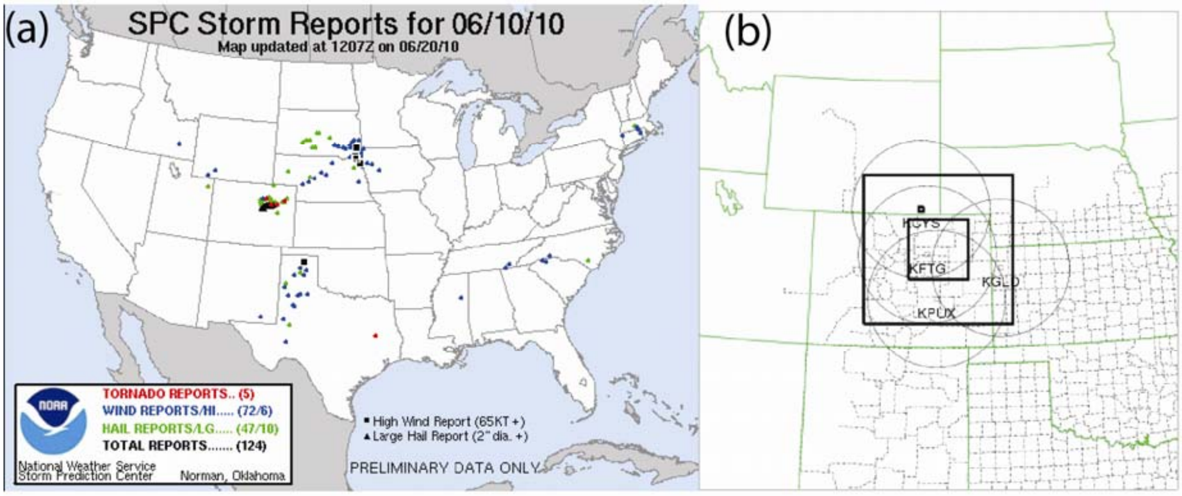

Fig. 5. Same as Fig. 1, but for Denver, Colorado tornadic storm event on June 10, 2010.

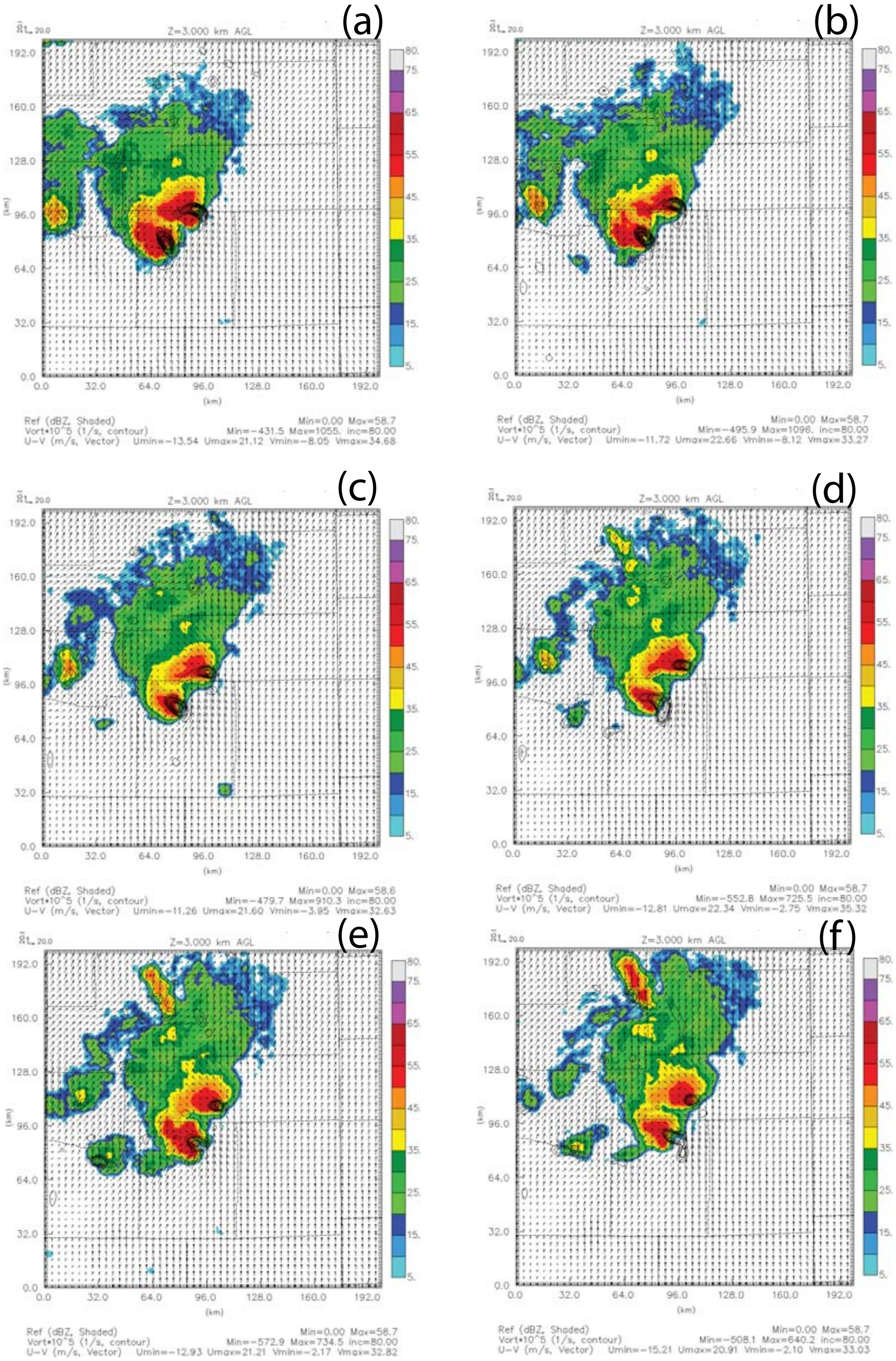

Fig. 6. The analyzed reflectivity, horizontal wind fields, and vortices at z=3 km using data from KPUX, KFTG, KCYC and KGLD radars valid at (a) 2210 UTC, (b) 2230 UTC, (c) 2250 UTC, (d) 2310 UTC, (e) 2330 UTC, and (f) 2350 UTC, June, 11 2009 near Denver, CO.

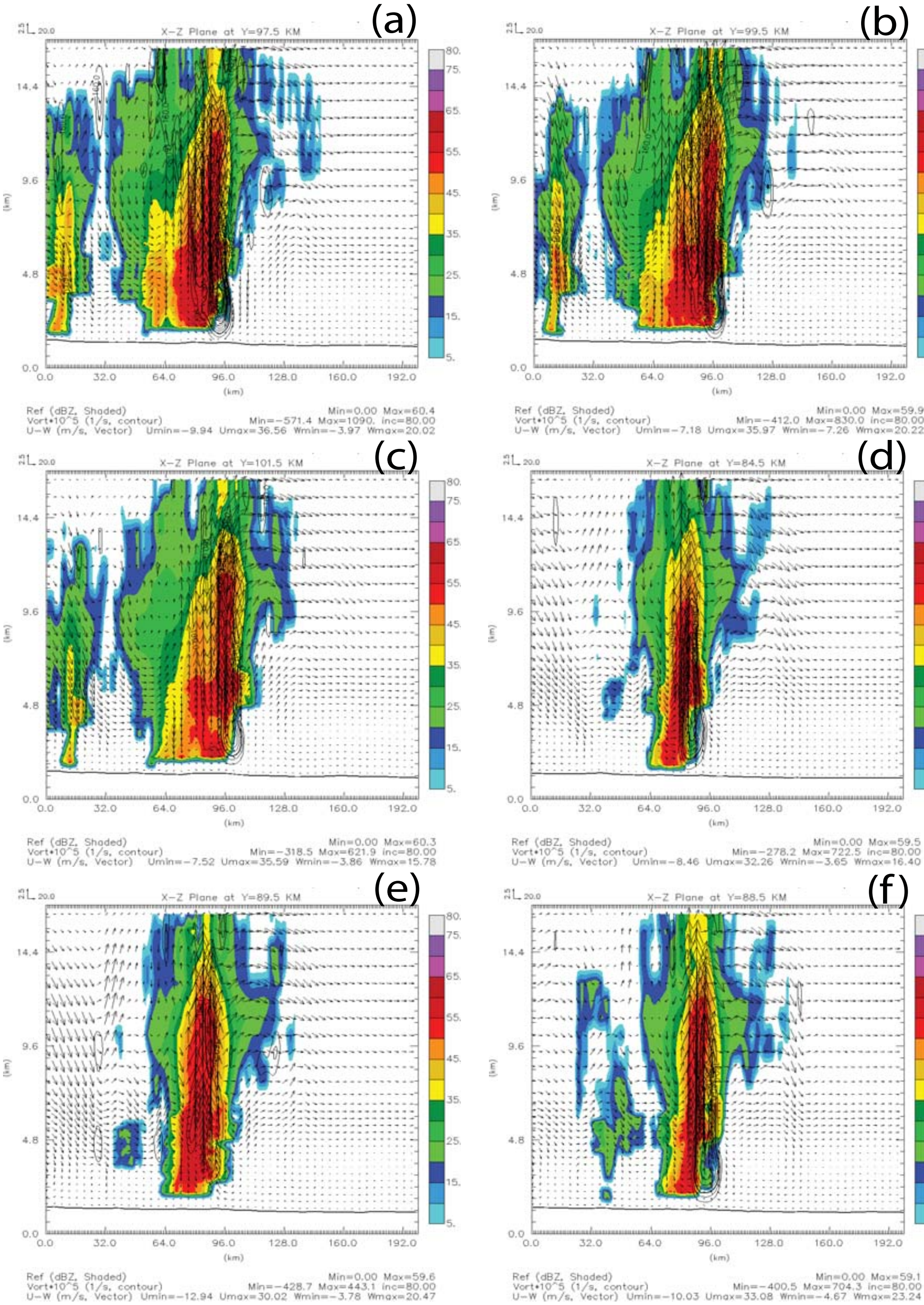

Fig. 7. Same as Fig. 6, but for vertical slice through the maximum vertical velocity.