Test of a Weather-Adaptive dual-resolution Hybrid 3DEnVAR and WRF-DART Analysis and Forecast System for Severe Weather Events

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1. Introduction

Increasing lead times for severe thunderstorm, tornado and flash flood warning is the mission of the NOAA Warn-on-Forecast (WoF) project which was funded in order to reduce the loss of life and property, injury, and economic costs of high impact weather. To reach this goal, convective-scale numerical weather prediction (NWP) modeling will play a big role thanks to the recent advances in both scientific research and computational power (Stensrud et al., 2009). The convective scale NWP model should include explicit microphysics scheme and run in high spatial resolution (1 km or less). The nonhydrostatic Advanced Research version of the Weather Research and Forecasting (WRF-ARW) model (Klemp 2004) developed at NCAR can be used for this purpose.

Another important component for improving convective scale forecasts is the development of multi-scale data assimilation schemes. These data assimilation schemes should take advantage of the high dense observations which can resolve internal structure of storms. The WSR-88D radars and GOES-R satellite data can satisfy this need. These high-resolution observations should also be assimilated into the convective scale NWP model in real-time with high frequency (5-15 minute cycles) quickly and accurately. To meet these requirements, Gao et al. (2013) developed a very efficient, real-time, weather-adaptive three-dimensional variational (3DVAR) analysis system for the WoF project to incorporate all available radar observations within a moveable analysis domain based on their early 3DVAR system which was designed for radar data assimilation at convective scale (Gao et al. 1999, 2002, 2004; Ge et al. 2010, 2012; Hu et al. 2006a, b; Stensrud and Gao 2010). Some key features of the system include: (1) incorporating radar observations from multiple WSR-88Ds with NCEP forecast products as a background state, (2) the ability to automatically detect and analyze severe local hazardous weather events at 1 km horizontal resolution every 5 minutes in real-time based on the current weather situation, and (3) the capability to identify strong mid-level circulations embedded in thunderstorms (Gao et al. 2013).

To assess the potential usefulness of the weather-adaptive real-time analysis system to warning operations, the 3DVAR system was formally tested and evaluated by forecasters who participated in the NOAA Hazardous Weather Tested (HWT) spring experiments from 2010 to 2013. During this time period, many severe weather events were successfully detected and analyzed automatically by the 3DVAR system. For all these experiments, the storm positioning system performed well. In general, strong circulations and vertical velocities associated with severe weather events were automatically identified and successfully analyzed. The analyzed wind structures of most storms not only matched quite well with synthesized reflectivity fields from multiple radars, but also agreed well with the archived storm reports from the NCEP Storm Prediction Center (SPC). The SPC storm reports provide locations and times for severe weather events including tornadoes, hail and strong wind events. The performance of this system as well its evaluation can be found in Gao et al. (2013), Smith et al. (2014), and Calhoun et al. (2014). However, utilizing these analysis results for initializing convective scale NWP model still remains a significant challenge because WSR-88D radars only observe radial velocity and reflectivity, and the 3DVAR system has limited ability to retrieve unobserved model variables from these radar data alone.

Improvements to 3DVAR are likely to come as we develop balance constraints for the convective scale (Ge et al. 2012) and optimize the incorporation of ensemble information into the 3DVAR system (Gao and Stensrud 2014). Lorenc (2003) first proposed a hybrid approach by combining variational and Ensemble Kalman Filter (EnKF) techniques. Many research articles about hybrid methods have been published in recent years. Since then, most of them have focused on synoptic-scale and mesoscale NWP (Barker et al. 2012; Buehner 2005; Buehner et al. 2010a, b; Wang et al. 2008, 2013; Zhang et al. 2013). Gao and Stensrud (2014) showed that hybrid methods have promise for convective-scale NWP as well. Specifically, they demonstrated that incorporation of ensemble-estimated covariance in a variational approach (3DVAR in this case) can significantly improve the accuracy of the assimilation of simulated radar data for a supercell storm. The conclusion holds even when just a few ensemble members are used and the estimated covariance contains severe sampling errors. This kind of frequently updated, numerical-model–based, probabilistic convective-scale analysis and forecast system could be used to support WoF operations. However, the EnKF method used in this system was preliminary.

Recently, a more advanced ensemble adjustment Kalman filter (EAKF; Anderson 2001) developed at the Data Assimilation Research Testbed (DART; Anderson and Collins 2007; Anderson et al. 2009) of the National Centers for Atmospheric Research (NCAR) was used to assimilate WSR-88D Doppler observations and Satellite derived cloud water path in storm-scale ensemble by the National Severe Storms Laboratory (NSSL) WoF team (Jones et al. 2013, 2014, 2016; Wheatley et al. 2012, 2015; Yussouf et al. 2015). Based on these studies, NSSL Experimental WoF System for ensembles (NEWS-e) was developed and tested during the past several years. To evaluate the capabilities of this system, storm-scale ensemble analyses and forecasts are produced for several severe weather events during 2013 and 2014 with 36 members (Wheatley et al. 2015; Jones et al. 2016). A series of 1-h ensemble forecasts are then initialized from these storm-scale analyses. Results indicate that for most cases, the ensemble forecasts were able to produce the strong low-level rotational characteristics of supercell thunderstorms, as well as other convective hazards. However, current real-time settings are only in convective-allowing mode (at 3 km horizontal resolution) and with a relatively small domain size. To further improve the system which can actually resolve storm internal structures for high-impact weather events in detail, horizontal resolution should be further refined. The horizontal grid-spacing around 1 km or less is a must. In other aspects, to improve the accuracy of convective scale ensemble forecasts and reduce the negative impact of model boundary, the size of ensemble members and model domain need further enlargement as well. It is certainly a challenge for us to justify how much computing resources should be distributed on each component: model resolution, domain size, or ensemble size for ensemble data assimilation and forecast.

As pointed out in Stensrud et al. (2009), it is essential that ensemble forecasts are utilized in the WoF concept to produce robust probabilistic forecast guidance. But relatively larger ensembles are generally needed to create a robust pure-ensemble DA system, as shown in Wheatley et al. (2015). Gao and Stensrud (2014) demonstrated that relatively small ensembles may be adequate for WoF-type forecasts. We believe that it may be appropriate to implement a WoF system that uses a hybrid approach of both 3DVAR and WRF DART ensemble data assimilation system. Gao and Xue (2008) found that the spatial scale of the background error covariance is typically smoother and larger than that of the analysis increment at model grid points. This allows us to use an ensemble of forecasts at a lower resolution (LR) to provide the background error covariance estimation for both an ensemble of LR analyses and a single Higher Resolution (HR) analysis. The idea was implemented by Japan Meteorological Agency recently in their LETKF system in a pre-operational environment (Fujita et al. 2010). Indeed, almost all major operational weather prediction centers in the world usually have two separate systems running – relatively LR ensemble prediction system (EPS) and a single HR model prediction. The HR model runs usually provide more detailed weather information in deterministic measurement but lack of uncertainty information, vice versa for ensemble runs. Therefore, it is appropriate to develop a dual-resolution hybrid ensemble and variational data assimilation and forecast system for convective scale weather within the WoF strategy. In this study, we introduce the dual-resolution data assimilation and forecast system using the WRF-ARW as the forecast model, and a hybrid data assimilation scheme using a convective scale 3DEnVAR system (NEWS-var) and a DART-based EnKF system (NEWS-e) developed for the WoF project. Some preliminary experiments will be presented.

The rest of this paper is organized as follows. Section 2 provides a brief description of the analysis and forecast system and experiment designs. Some preliminary experiment results are reported and assessed in section 3. We conclude in section 4 with a summary and future work.

2. The overview of the analysis and forecast system

The DART data assimilation system developed at NCAR uses an EnKF (Evensen 1997) algorithm to update the probability distribution of the atmospheric state given a set of observations and their associated error based on a prior estimate of the state's probability distribution. The prior probability distribution is estimated from the statistics of an ensemble, which incorporates flow-dependent covariance information. Further details on the DART ensemble Kalman filter algorithm can be found in Anderson and Collins (2007) and Anderson et al. (2009). In the WoF application, 36 ensemble members are used.

The 3DVAR system designed especially for radar data assimilation at the convective scale was originally developed at Center for Analysis and Prediction of Storms (CAPS) and was further improved at National Severe Storms Laboratory (NSSL, Gao et al. 1999, 2002, 2004; Hu et al. 2006a, b; Ge et al. 2010, 2012; Stensrud and Gao 2010; Xue et al. 2003). It applies weak constraints which are suitable for convective storms in a different manner than that of other 3DVAR systems developed for large scale applications. In this convective scale 3DVAR scheme, cross-correlations among state variables are not included in the background error covariance **B**; certain balance between analysis variables is realized by incorporating weak constraints in the cost function (Gao et al. 2004; Ge et al. 2012). The use of the weak mass continuity constraint links the three components of wind field by the 3DVAR method in response to the assimilation of the radial velocity observations, and the use of model equation constraint couples the other model variables and makes sure the analysis variables balance with each other. The spatial correlation is modeled by a recursive filter proposed by Purser et al. (2003). A method for directly assimilating reflectivity with hydrometeor classification was proposed recently for this scheme (Gao and Stensrud 2012). In this method, a modified forward operator for radar reflectivity is developed which classifies the hydrometeor species based on the background temperature from a numerical weather prediction. Recently, the 3DVAR system was upgraded to use flow-dependent background error covariances derived from a set of ensemble forecasts, this system is named 3DEnVAR (Gao and Stensrud 2014).

The hybrid data assimilation uses both EnKF method, such as the above described DART and a variational method, such as the 3DEnVAR as two data assimilation components (Lorenc 2003). The two data assimilation systems can be coupled in two ways: the DART system provides flow-dependent background error covariances for the deterministic 3DEnVAR system (one-way hybrid, see). At the same time, the analysis from the 3DEnVAR can be used to re-center the ensemble mean for the DART members (two-way hybrid). As a first step for the real-time tests, only one-way hybrid will be implemented in this study. That is, only the ensemble derived flow dependent background error covariance from DART is used in the 3DEnVAR. In the analysis and forecast system, the use of a convective scale NWP model is an essential part. The WRF-ARW model is chosen for this purpose as it is a widely used tool for convective-scale research and prediction. The system has a variety of process parameterization schemes (e.g., radiation, PBL and microphysics) that are suitable for convective scale prediction.

In the analysis component, the convective scale LR ensemble analyses are produced using WRF-DART on 250x250 horizontal points at 3 km resolution, and 51 vertical levels, while the single HR analyses are produced using the 3DEnVAR on 500x500 horizontal points at 1.5 km resolution, and 51 vertical levels. Both analyses are produced every 15 minutes start from 1800Z until 0300Z each day during the 5-week HWT spring experiment period (From May 8, 2017 – June 9, 2017). The LR 36-member ensemble forecasts start from 36 distinct initial conditions provided by the High-Resolution Rapid Refresh Ensemble (HRRRE) from the Earth System Research Laboratory (ESRL). The lateral boundary conditions for the ensemble are provided from a 9-member 15Z forecast, while the single HR uses initial and boundary conditions provided by the deterministic member of the High-Resolution Rapid Refresh (HRRR) of ESRL. The LR ensembles maintain spread using the adaptive inflation within DART (Anderson 2009) with additional additive noise introduced locally when the innovation exceeds 25 dBZ (Dowell and Wicker 2009; Sobash and Wicker 2015). The observation used includes WSR-88D radar data and its derived VAD winds, satellite derived cloud water path from GOES-13 (GOES-16 product in the future) and surface observations from surface aviation observation (SAO), Oklahoma mesonet and west Texas mesonet if the analysis and forecast domain covers that area.

For the forecast component, both LR ensemble and HR single forecasts are launched at 1900Z and forecast length is 4 hours. Starting at 2000Z, three hour ensemble forecasts are launched at the top of each hour and 90 minutes forecasts are launched at the bottom of each hour until 0300Z (). In the current hybrid data assimilation system, both the static background error covariances (modeled by the recursive filter) and ensemble covariances are used with ensemble covariances has 60% contribution to the total covariances. In case that any of the ensemble forecast/analysis fails, the system will automatically revert to use full static background error covariance as a fault-tolerance measure. The analysis and forecast domain is weather-adaptive and is chosen each day based on the convective outlook from SPC's convective outlook (see http://www.spc.noaa.gov/products/outlook/).

During the 5-week spring experiment period in 2017, there are three major severe weather outbreak periods. They are from May 8 to May 10, from May 16 to May 18 and from May 25 to May 27. In this study, we will present preliminary results for the single HR analysis and deterministic forecast from three hazardous weather events on May 10, May 16 and May 26 (one day from each period) respectively. The solid verification results are not presented in this conference and will be reported in future study.

3. Some Preliminary Results

As discussed early, the reliability and accuracy of both DART and the 3DEnVAR system for severe thunderstorm analyses and forecasts have been illustrated by a number of numerical experiments with both simulated and real data cases (e.g., Jones et al. 2013, 2014, 2016; Wheatley et al. 2012, 2015; Yussouf et al. 2015; Gao et al. 1999, 2004; Hu et al. 2006a, b; Stensrud and Gao 2010; Schenkman et al. 2011; Zhao et al. 2012; Gao and Stensrud 2014). To assess the potential usefulness of the hybrid analysis and forecast system to warning operations, the images produced by the experiments are posted in real-time to NSSL website at (http://nssl.noaa.gov/projects/wof/) to facilitate access within the HWT and other interested users. Here we only present the results produced by the single HR deterministic model runs, i.e. the control member runs. The performance of the system on three tornadic supercell cases observed during this time period is examined below, we focus especially on May 16 case which produces Elk City EF-2 tornado.

a. May 10th tornadic supercell storm in Texas panhandle

The first case is a tornadic supercell that occurred on 10 May 2017 over the Texas Panhandle. Though there were many severe weather events in US mid-west region during that day (), our analysis and forecast domain is located mainly near Oklahoma and northern Texas area. From SPC storm reports, one tornado touched down and large hail was reported in the eastern Texas panhandle starting from 2000Z through late that evening (*b*). Our real-time forecast experiments are carried out during that period. A 3-hour forecast started from 2000Z captures the major thunderstorm which produces the large hail and tornado. After 45 minutes later, the low-level rotation of the supercell becomes very strong, and the tornado has touched down by this time (*a*). The rotation remains very strong for about 1 hour, and the rotational track agrees well with the hail and tornado reports produced by SPC (*b*). The supercell remains strong until the end of forecast length at 23:00 Z, but the rotation weakens beginning at 21:30 Z (*c*, *d*). In general, our forecast forecasts this supercell accurately during the 3-hour forecast started from 2000Z. The next forecast started from 2100Z also represents the threat fairly well. Since it is after the tornado touched down, the figure is not shown here. The forecasts started from 0100Z, 0200Z and 0300Z, however, missed the supercell storm which produces southwestern Oklahoma tornadoes (also not shown).

b. May 16th tornadic supercell storms in Northeastern Texas and southwestern Oklahoma

During May 16, 2017, there were many severe weather events in Mid-West US. Again, our analysis and forecast domain focuses on three states: Kansas, Oklahoma and Texas based on SPC convective outlook. In reality, most of severe weather events, especially for those which produced tornadoes and large hail were located in these three states. The low panel of shows three major tornado damaging paths produced near boundaries of Oklahoma and Texas, Kansas and Oklahoma. Two major supercells across the Oklahoma and Texas border each produced a swath of tornadic damage associated with over a dozen of tornadoes (*b*). The south supercell actually produced an EF-2 tornado which hit the Elk City Oklahoma. The after-event survey indicates that many buildings were destroyed including one dead and dozen of injuries (**Error! Reference source not found.**).

Our 3-hour forecast started from 2100 Z captured multiple storm structures which match with the SPC storm reports well. The three-hour control forecast from 2100Z suggests the southern-most supercell is the most significant threat during the forecast period. It is interesting to note that in the real time NEWS-e forecast from 2100Z, ensemble forecasts have the northern storm producing the strongest rotation (figure not shown), and only weak rotation is predicted for the southern storm. Here in the control (*Fig. 7*), the reverse is predicted. The southern storm control forecast predicts several periods of intense rotation followed by weaker rotation, perhaps indicating the storm will cycle several times over the three-hour forecast. This is consistent with the observed tornadic activity. The first period of tornadic activity with the southern storm is indicated in *Fig. 7a*-*b*, just west of the OK-TX border. The rotation in the predicted storm weakens after crossing the border (*Fig. 7c*), but eventually ramps back up near Elk City and points northeast (*Fig. 7d*). The strongest tornado of the day is near Elk City (EF-2) which is supported by the mid-level rotation and the composite low-level vertical vorticity (0-2 km) and the composite maximum vertical velocity (*Fig. 8*). However, as in most storm-scale forecasts (including the ensemble forecasts), the Elk City storm is moving too quickly to the northeast and therefore the predicted threat arrives 30-45 minutes too soon. In general, all these predicted variables reveal a strong supercell which has capability to produce tornadoes and large hail. The later hour forecast (not shown) started from 2200 Z produces very similar forecast results. We are engaging in further analyses about this case and the results will be reported in a separate paper soon.

c. May 26th tornadic supercell storms in Northeastern Colorado and Northwestern Kansas

The third case examined is a series of severe weather events that occurred at the northeastern Colorado and northwestern Kansas on 26 May 2017 (*Fig. 9*). The severe weather events including tornadoes and large hail storms occurred in Colorado from 2200 Z to 0010 Z and the severe weather

events in West Kansas occurred from 0400 Z to 0700 Z. We focus our examination of the short-term forecasts during these two periods.

The forecast for the first period started from 1900 Z until 2300 Z. It can be seen that there are a strong rotation track and a maximum updraft (composite) track during this forecast period. These tracks qualitatively agree well with the tornado reports in *Fig. 9*. At the end of the 4-hour forecast, the supercell denoted by a big reflectivity core (*Fig. 10a*) and remains strong throughout the forecast. This supercell storm moves to the boundary of Colorado and Kansas slowly and produces another tornado about two hour later. A later forecast starting at 0300Z for 3 hours later is also shown in Fig 10. *Fig. 10b* and *d* reveals that there are some relatively strong rotations during these 3-hour forecast period. Upon closer inspection the storm track is biased northward relative to the reports in the SPC database. The SPC storm reports reveal a storm cluster moving toward the south-east-east, while in the forecast, the storm cluster moves east-northeast.

4. Summary and concluding remarks

In this study, a real-time, weather adaptive hybrid 3DEnVAR and WRF-DART analysis and forecast system based on the WRF-ARW forecast model have been developed and tested. We intend to provide weather-adaptive ensemble-based physically-consistent gridded analysis and forecast products to forecasters for making warning decisions in a timely manner.

The analysis and forecast domain is determined each day based on SPC's convective day 1 outlook product so that the forecast then focuses on the expected severe weather for that day. Both the ensemble-based WRF-DART system and the 3DEnVAR system are continuously cycled using a 15-minute data assimilation system from 1800 Z to 0300 Z each day. The dual resolution strategy uses the WRF-DART ensemble background errors at 3 km grid spacing, while the 3DEnVAR analysis uses a 1.5 km grid. Then the 36 LR ensemble members and one deterministic HR analyses are used to create a new forecast twice an hour. The dual system was tested during the 2017 Hazardous Weather Testbed (HWT) Spring Experiment period. Presented here are a few preliminary results from the HR deterministic forecasts. Although still in its early development stage, the system performed reasonably well with the HWT preliminary testing as several severe weather events were successfully forecasted hours in advance. This study represents our initial efforts in the assessment of using hybrid 3DEnVar in severe weather warnings within the WoF project. The eventual goal is to help meteorologists making better forecasts for severe weather events beyond 1 hour using convective NWP models to provide better warning information to the public, ultimately saving lives and reducing property damage.

However, there remain many scientific and technical challenges. Occasionally the control forecast system is not stable. At times multiple spurious storm cells develop within the analysis and forecasts. Recent tests indicate that the development of those spurious cells may be attributed to the cloud analysis package adding too much moisture. This is likely to be solved or lessened when radar reflectivity data is assimilated in a variational framework directly (Gao and Stensrud, 2012). We plan to continue the sensitivity tests with various parameter adjustments and hopefully further improve the performance of both the analysis and the forecast systems.

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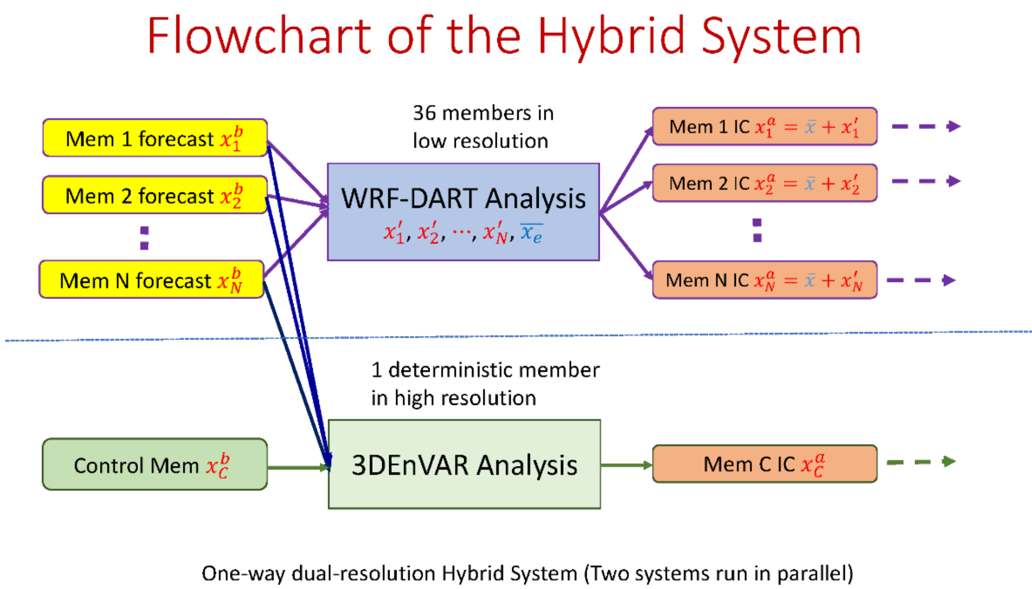

Fig. 1 One cycle segment for the workflow of the hybrid 3DEnVar and WRF-DART system

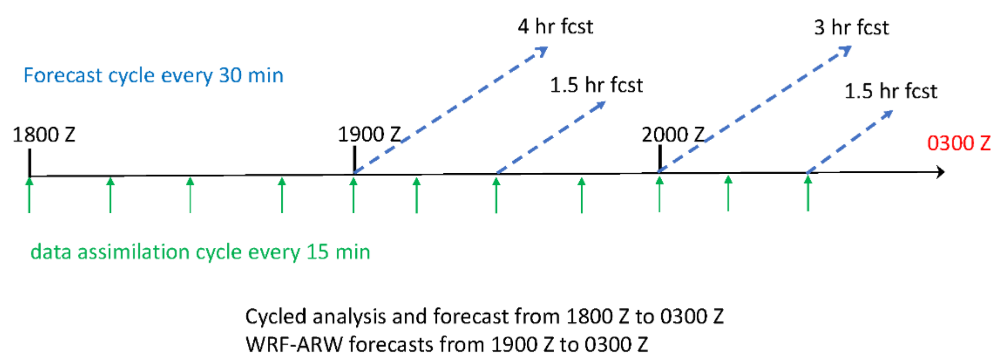

Fig. 2 The Flowchart of the real-time run settings during Hazardous Weather Testbed spring experiments in 2017.

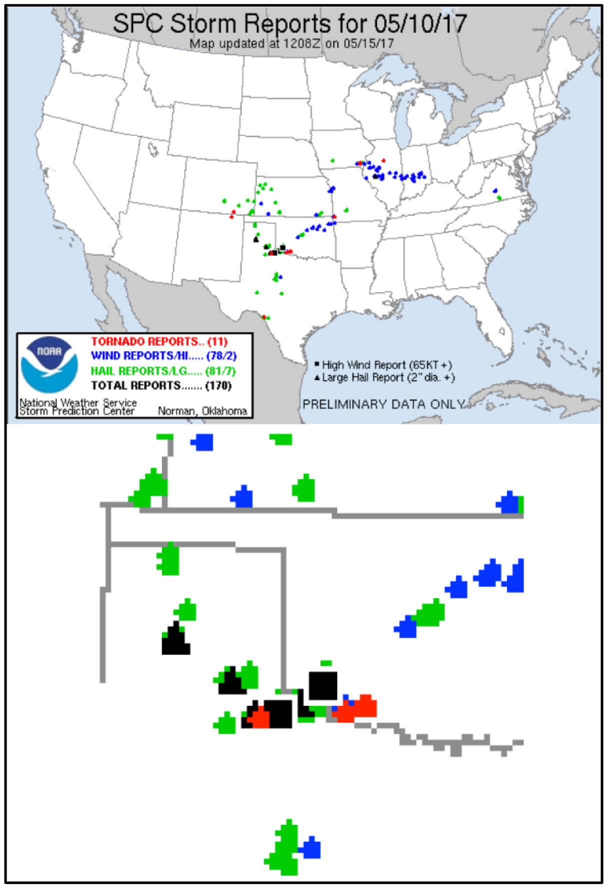

Fig. 3 *The storm report from Storm Prediction Center (SPC) about severe weather events on May 10. The upper panel is the report for US CONUS domain and the lower panel is the zoom-in domain for the analysis and forecasts that covers partial of Kansas, Oklahoma and Texas.*

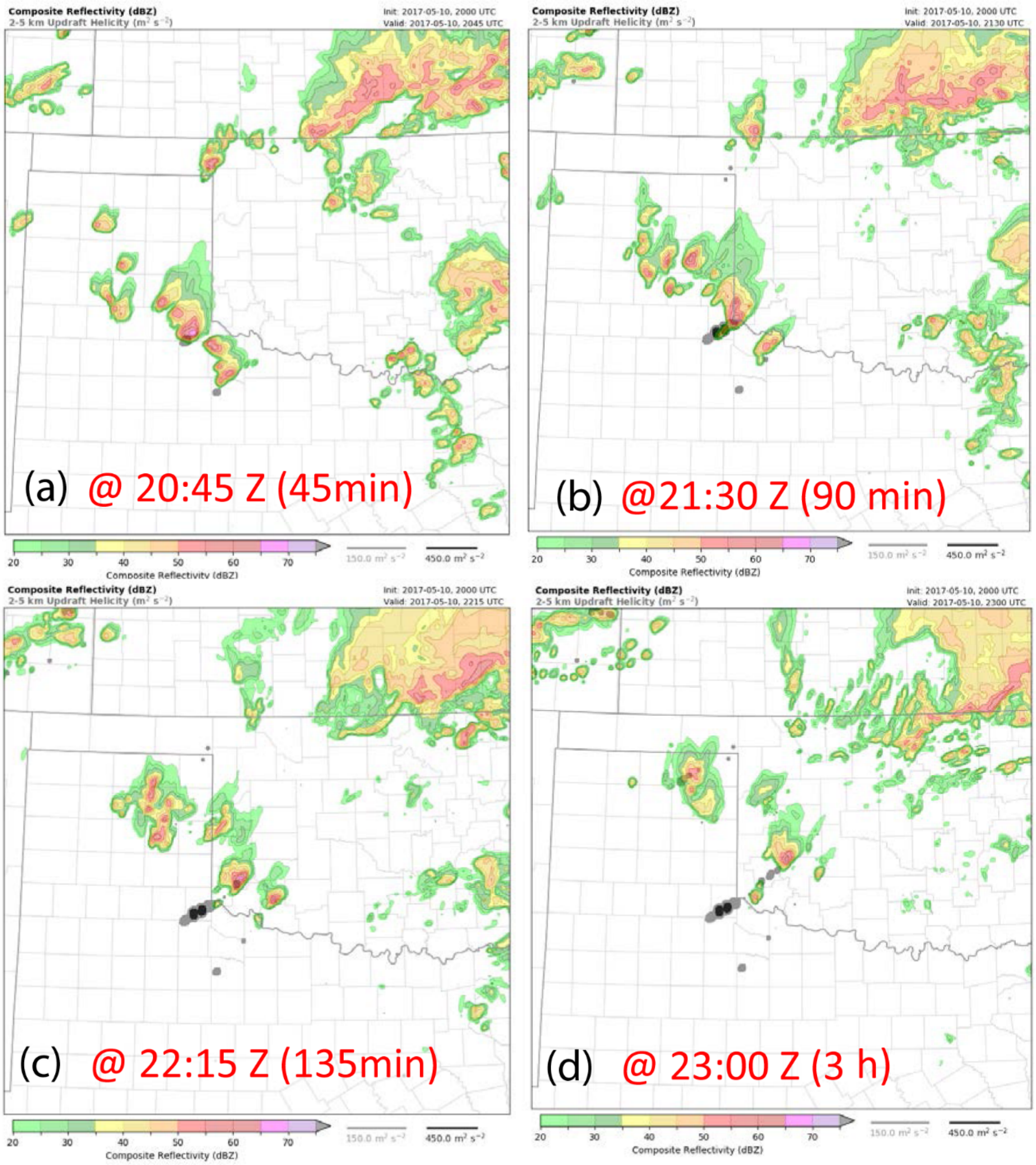

Fig. 4 The track of updraft helicity between 2- 5 km above the ground (black contours) for the 3-hour forecast period starting from 2000 Z, 10 May 2017. The composite reflectivity (color shaded) are also shown at (a) 2045 Z, (b) 2130 Z, (c) 2215 Z, (d) 2300 Z.

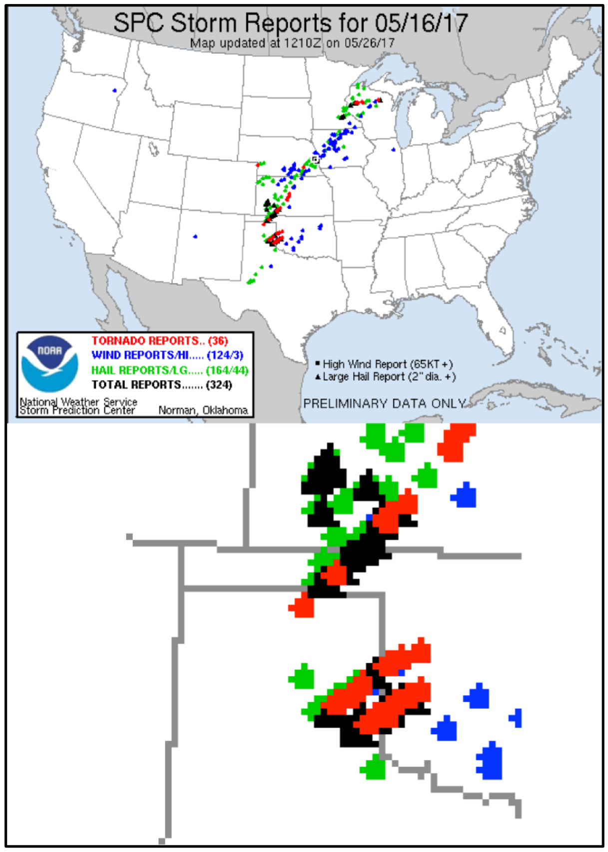

Fig. 5 Same as Fig. 3 but for 16 May 2017 Elk City tornadic thunderstorm case.

Fig. 6 May 16, 2017 Elk City, Oklahoma EF-2 Tornado.

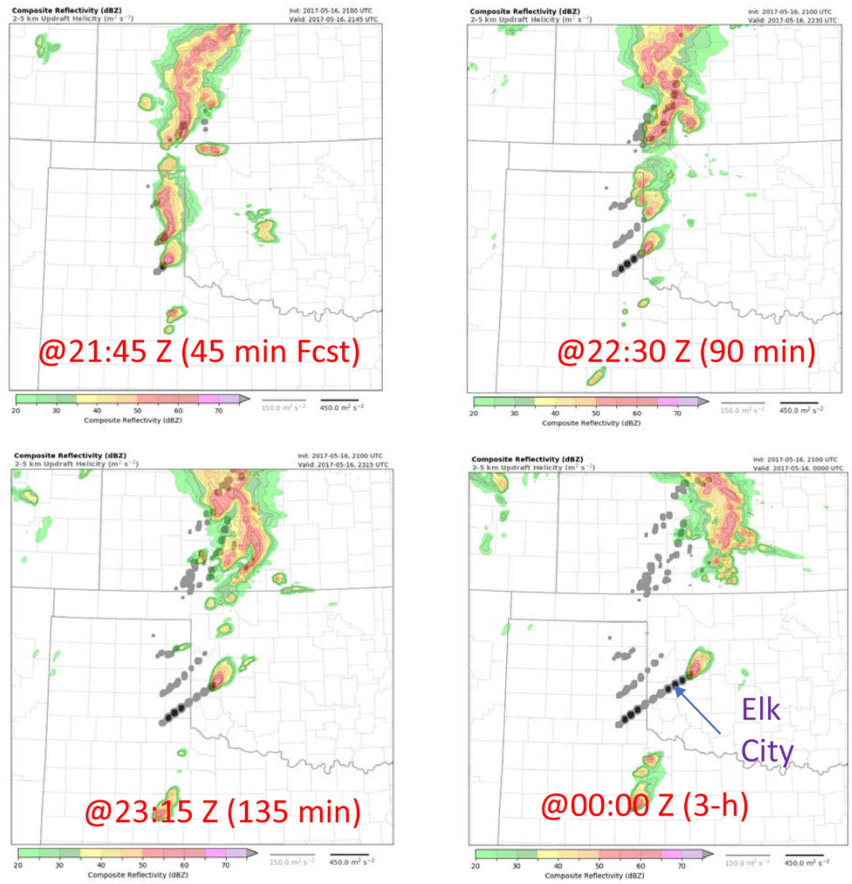

Fig. 7 . Same as Fig.4, but for Elk City, Oklahoma tornadic thunderstorm event on 16 May 2017 at (a) 2145 Z, (b) 2230 Z, (c) 2315 Z, (d) 0000 Z.

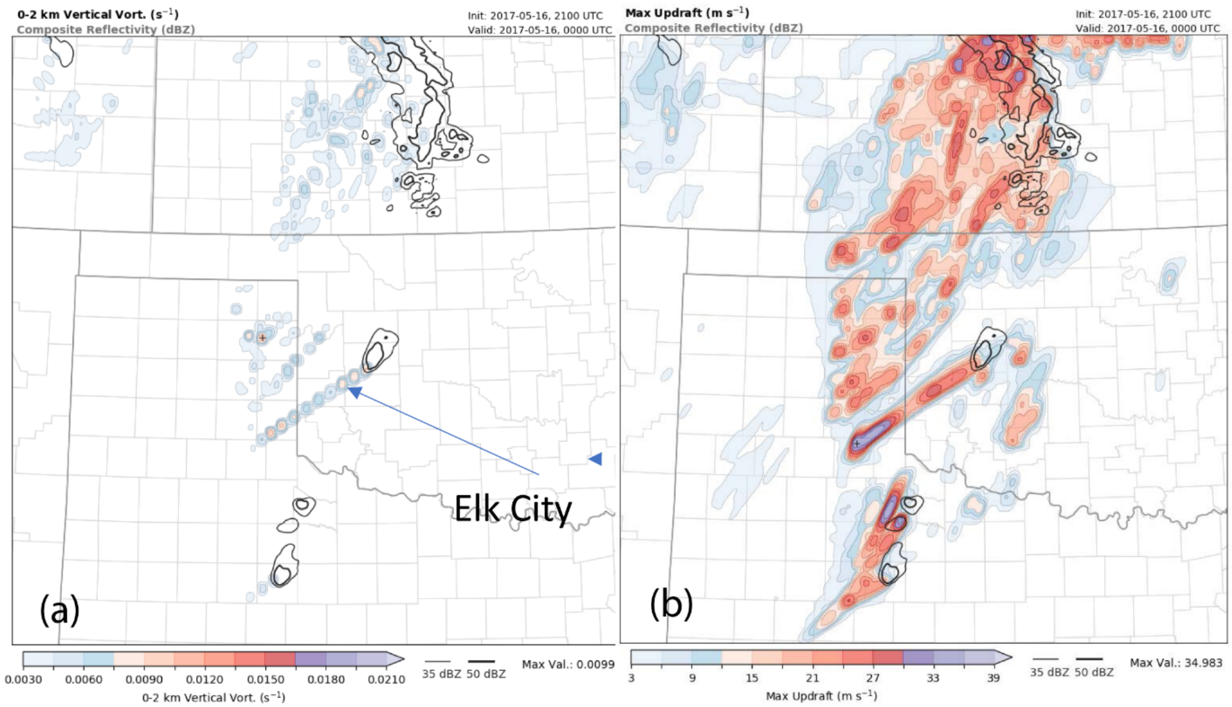

Fig. 8 The tracks of (a) Composite low level vertical vorticity (0-2km), and (b) Composite maximum updraft for 3-hour forecasts. The composite reflectivity at 0000Z are shown in both panels as black contours.

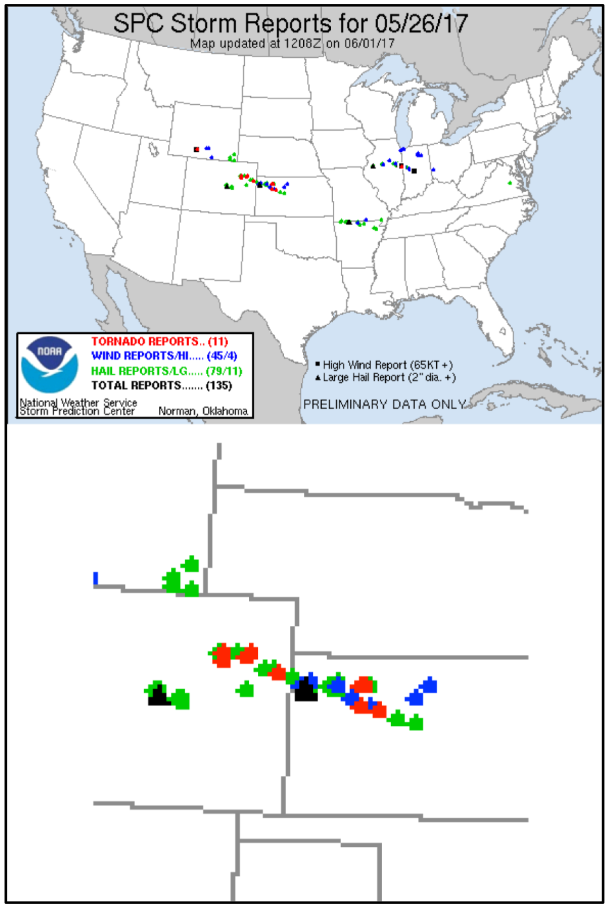

Fig. 9 Same as Fig. 3, but for tornadic supercell event near boundary of Colorado and Kansas on May 26, 2017.

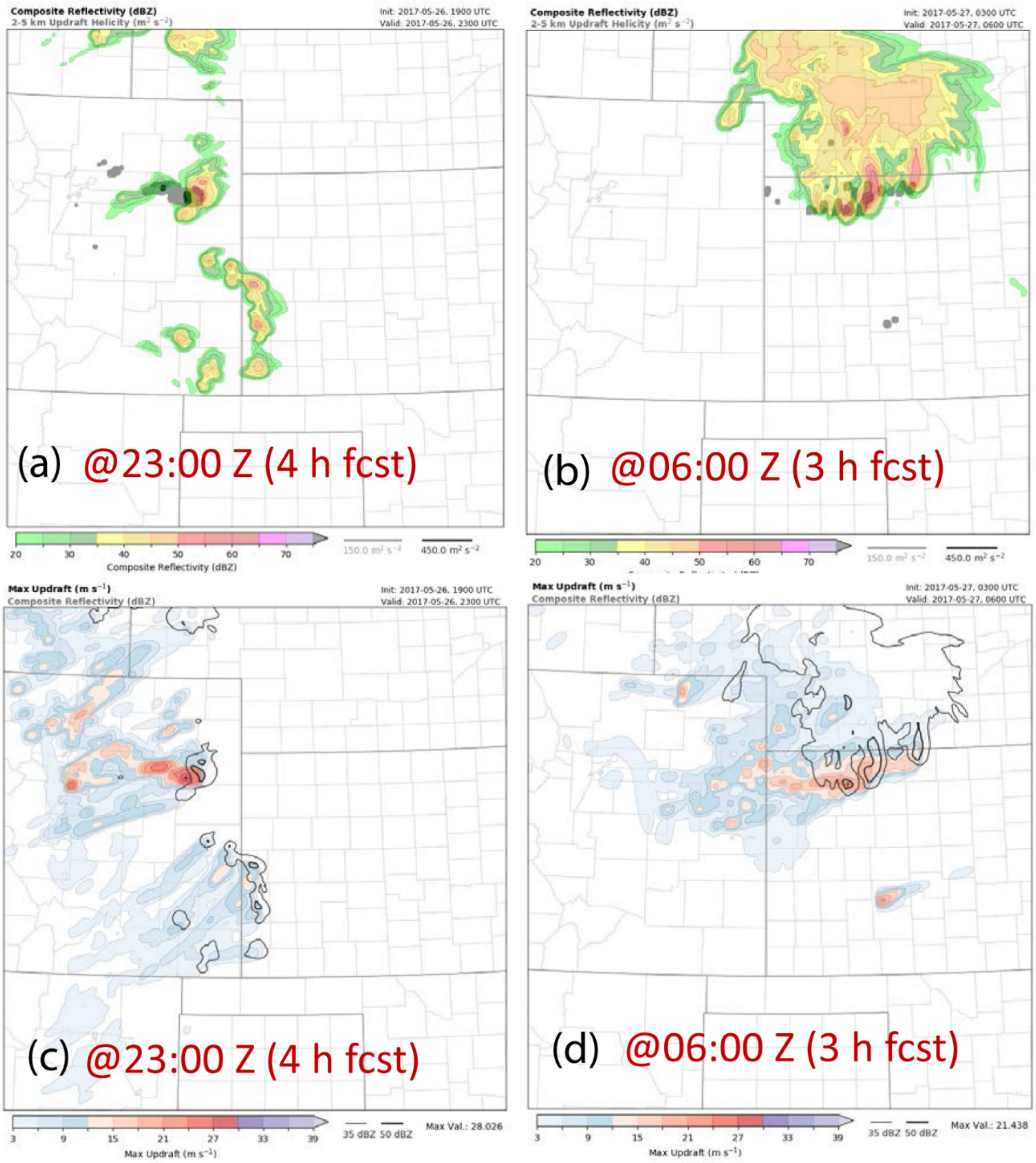

Fig. 10 Tracks of the updraft helicity between 2- 5 km above the ground
(a) 4-hour forecasts starting from 1900 Z; (b) 3-hour forecasts starting from 0300Z.
And the composite maximum updraft
(c) 4-hour forecasts starting from 1900 Z; and (d) 3-hour forecasts starting from 0300Z.