THE DENVER MESOSCALE FORECAST EXPERIMENT: THE CASE OF THE 21 JULY 1993 NORTHEAST COLORADO TORNADOES

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Abstract

The occurrence of two significant tornadoes in northeast Colorado during the Denver Mesoscale Forecast Experiment provided an opportunity to assess forecast methodology and new data sets in a real-time, operational environment using a functional prototype Advanced Weather Interactive Processing System (AWIPS) workstation and Doppler radar. One dedicated mesoscale forecaster prepared an outlook prior to the event and issued warnings during the event based on data available from the Mesoscale Analysis and Prediction System (MAPS), the Local Analysis and Prediction System (LAPS) and the WSR-88D Doppler radar. It is shown that a logical and scientifically sound approach to forecasting using new high resolution data sets can provide a significant and practical lead time in assessing a potential severe weather event at the local office level.

1. Introduction

On 21 July 1993, a number of tornadoes were spawned by two supercell thunderstorms on the northeast plains of Colorado, east of Denver (DEN). Although the tornadoes occurred over open country and produced minimal damage, at least two of them were quite significant and potentially very destructive based on eyewitness accounts.

Forecasting this event was challenging as the environment in which these thunderstorms initially developed was not conducive to supercell type storms. However, as the storms moved east, the thermodynamic characteristics of the environment and the vertical wind shear profile they interacted with were more favorable for supercell thunderstorms. These storms developed supercell characteristics after moving into that air mass environment.

Another important aspect of the storms' evolutions was their formation during a mesoscale forecasting experiment which was ongoing at the DEN National Weather Service (NWS) Forecast Office at that time. This experiment was designed to take full advantage of the functional prototype Advanced Weather Interactive Processing System (AWIPS) workstation available to forecasters as part of an NWS modernization risk reduction exercise. The workstation provides forecasters, in real time, easy access to and the ability to integrate visually an enormous number of advanced data sets including high resolution mesoscale analyses and forecasts, satellite imagery, Doppler radar and wind profiler data, as well as conventional surface and rawinsonde observations and gridded, synoptic-scale numerical model output.

This paper will describe how some of the new data sets available on the workstation were used by the mesoscale forecaster on 21 July 1993 to diagnose and predict the evolution of the convective weather observed on that day.

2. The Mesoscale Forecaster

One element of the mesoscale forecasting experiment during the 1993 convective season was a dedicated forecaster working from 1000 to 1800 local time each day. This mesoscale forecaster was responsible for issuing a daily outlook regarding the potential for severe weather (hail 3/4 inch diameter or larger, winds 50 knots or greater, and/or tornadoes) to occur during the afternoon and evening in northeast Colorado. This forecaster also issued all appropriate severe weather warnings for DEN's County Warning Area (CWA), which covers northeast and north central Colorado. Because convection in northeast Colorado generally exhibits a pronounced diurnal trend, the mesoscale forecaster normally had sufficient time prior to convective development to diagnose properly the synoptic, mesoscale and local environments over the area. Furthermore, time was available to evaluate output from a mesoscale forecast model to determine the likelihood, strength, timing and location of convection for the afternoon and evening hours.

3. Local and Mesoscale Analysis and Prediction Systems

Two very powerful tools that significantly aided the mesoscale forecaster on this date were the Local Analysis and Prediction System (LAPS; McGinley et al. 1991; McGinley 1989) and the Mesoscale Analysis and Prediction System (MAPS; Miller and Benjamin 1992; Benjamin et al. 1991). Each system will now be briefly described.

a. LAPS

LAPS was designed to fill the analysis void on the meso-β scale, which covers a spatial scale from 20–200 km and time scales of a few hours (Orlanksi 1975). It utilizes and merges new and standard data sources and is capable of being run within the local NWS office environment.

The output from LAPS comprises gridpoint fields of surface, tropospheric and lower stratospheric wind, pressure (height), temperature, moisture, cloud base, top and coverage, precipitable water, radar reflectivity, and a number of derived products including changes of atmospheric variables, vertical motion and surface-based convective available potential energy (CAPE) and convective inhibition (CIN). The data is analyzed to a grid with 10 km horizontal and 50 mb vertical resolution covering all of eastern Colorado. All products are available hourly.

Data ingested into LAPS include surface aviation and mesonet observations, Doppler radar volume scans, vertical wind profiler measurements, radiometric profiles of moisture and temperature, GOES visible and multichannel imagery and sounding data, and automated aircraft reports. The use of radar and satellite data provides enough observational density, supplementing surface aviation observations and profilers, to justify a 10 km resolution.

LAPS output can be displayed on the prototype AWIPS workstation in plan view, time series or cross section format. Time-height sections can be created for a single point or spatial cross sections can be made between any two points. Spatial cross sections can also be looped over time to monitor the evolution of parameters in a vertical plane. Vertical soundings (skew-T plots) can be constructed for any point in the LAPS domain and manipulated in a manner similar to that provided by the Skew T/Hodograph Analysis and Research Program (SHARP) workstation software (Hart and Korotky 1991).

LAPS data are very frequently displayed on the workstation by overlaying them on other data sets, especially surface observations, radar reflectivity and velocity, and satellite imagery. These combined images are then animated and automatically updated on the screen as new data arrive.

b. MAPS

The MAPS package provides DEN NWS forecasters with complete hourly objective surface analyses and three-hourly upper-air analyses. Three- and six-hour forecasts are available every three hours, with nine- and twelve-hour forecasts available from 0000 and 1200 UTC analyses. The MAPS model is described in Bleck and Benjamin (1993).

Data from surface observations, rawinsondes, wind profilers, and automated aircraft reports are incorporated into MAPS analyses and forecasts. Boundary conditions are provided by the NWS Nested Grid Model (NGM), the forecast component of the Regional Analysis and Forecast System. The data are analyzed and forecast on a 60 km horizontal grid covering the continental United States using 5 terrain-following sigma layers and 19 isentropic levels.

MAPS data are available on the prototype AWIPS workstation on isentropic, isobaric and sigma surfaces. This information is quickly and easily accessed in real time using application programs which display output in either plan view or cross section formats. Spatial and time-height cross sections using MAPS data are created the same way as with LAPS output with the additional ability of combining analyzed and forecast fields in the same cross section. Analyzed and forecast soundings are also available, which can be manipulated as previously discussed. MAPS data are frequently integrated with numerous other data sets available on the workstation, such as satellite, upper-air and surface plots, and profiler winds. As with LAPS, animation of the MAPS data overlaid with the other data sets is also a key element in its usefulness.

One of the major strengths of MAPS is the use of isentropic coordinates. Although problems exist with isentropic coordinates (e.g., little or no resolution in dry adiabatic layers) the many advantages typically outweigh any difficulties which may be encountered. Several of the advantages of an isentropic framework have been cited by Moore (1987). These include better resolution of frontal zones (both upper and lower tropospheric), more coherent patterns of moisture transport, more direct assessment of vertical motion, and with the use of cross sections, a quick evaluation of frontal location and static stability.

4. Initial Diagnosis on 21 July 1993

The first step the mesoscale forecaster takes in preparing the forecast is to complete a thorough diagnosis of the synoptic, mesoscale and local environments which will influence the weather over northeast Colorado. As noted by Doswell and Maddox (1986), this diagnostic step is crucial in any forecast. Tools available to the mesoscale forecaster include surface observations, rawinsonde observations, satellite imagery, wind profilers, surface mesonet observations, LAPS, MAPS and the WSR-88D.

The MAPS 200-mb analysis at 1200 UTC 21 July 1993 (subtract 6 hours for MDT) depicted an 85 kt jet axis stretching from northwest Arizona across Utah into southwest Wyoming (Fig. 1). The stronger flow associated with the jet axis was also reflected in the 500-mb and 700-mb wind fields (not shown). Satellite imagery (not shown) indicated that the jet and an associated short-wave trough were providing a favorable environment for convection as a band of showers and thunderstorms was ongoing over eastern Utah and western Colorado at this time. In addition to the ascent associated with the jet streak and short-wave trough, low static stability was also analyzed over Colorado. Figure 2 depicts 8–9 °C km^{-1} lapse rates in the 700-500 mb layer ahead of the trough, indicative of nearly dry adiabatic conditions in this layer. The evolution of this field was shown by Doswell et al. (1985) to be a useful tool in forecasting convection. Low pressure at the surface and 850-mb levels was analyzed by MAPS in southern Wyoming (not shown). This feature was important in creating low-level southeasterly synoptic-scale flow into most of northeast Colorado.

On a smaller scale, the environment across northeast Colorado that morning consisted of two strongly contrasting air masses. The 1200 UTC DEN sounding was rather dry with a weak vertical wind shear profile (Fig. 3). This was representative of the environment along the Front Range, near the longitude of DEN. Closer to the Kansas state border, satellite and surface observations indicated a low stratus layer and dryline (not shown). The horizontal and vertical extent of this stratus

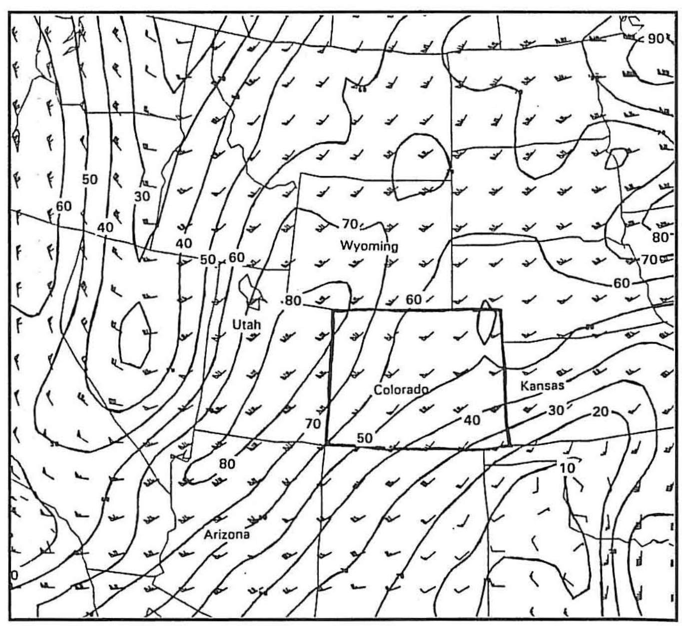

Fig. 1. 200-mb wind (flag = 50 kt, full barb = 10 kt, half barb = 5 kt) and isotach analysis from MAPS at 1200 UTC 21 July 1993.

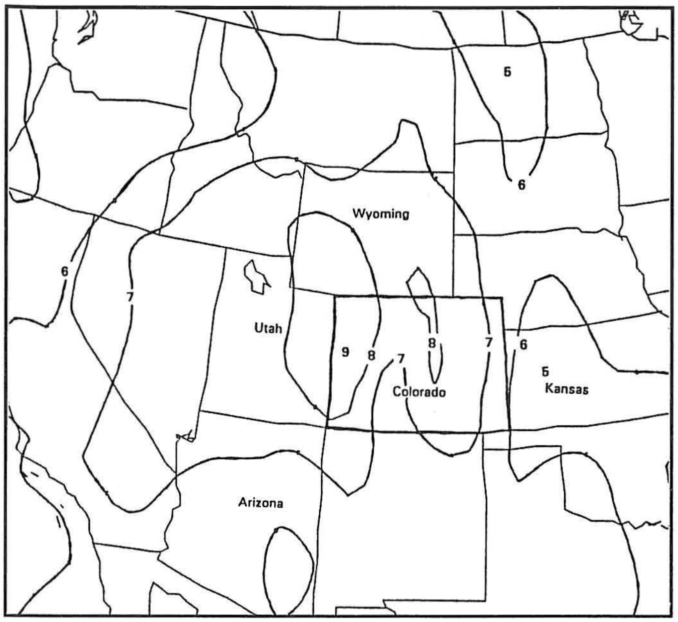

Fig. 2. 700-500 mb lapse rate (°C km^{-1}) analysis from MAPS at 1200 UTC 21 July 1993.

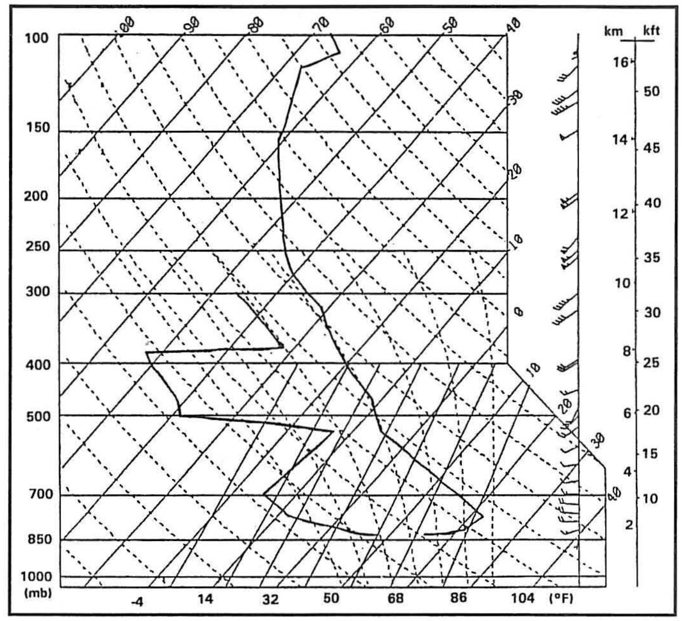

Fig. 3. Skew T/ln p plot of 1200 UTC 21 July 1993 DEN upper-air sounding. Winds as in Fig. 1.

layer was well depicted by a LAPS cross section of relative humidity at 1600 UTC across northeast Colorado (Fig. 4, see Fig. 5 for the location of the cross section). The position of the dryline is shown in the cross section as is the implied strong convective instability (very dry air above the stratus layer). The real-time utility of LAPS based in part on its assimilation of satellite data is especially apparent here. Only two stations, Limon and Akron, Colorado, regularly report surface data over a 40,000 km^2 area in northeast Colorado. The nearest soundings are DEN and North Platte, Nebraska (LBF). DEN was not located in the moist air and LBF is about 400 km to the northeast of DEN. The 1600 UTC LAPS surface wind analysis (Fig. 5) showed moderate southeast winds over a large portion of northeast Colorado with weak downslope winds closer to the mountains (nearer to DEN). This wind analysis, in addition to the rawinsonde observation, hinted at the fact that a lee trough was beginning to develop just east of the mountains, perhaps being an extension of the low over south central Wyoming.

To reiterate, on the synoptic-scale a middle to upper-level, short-wave trough and jet streak were evident to the west of the forecast area. These features were associated with a wind shear profile more favorable for deep moist convection and the same or lower static stability than was present over northeast Colorado at 1200 UTC. On the mesoscale, two air masses resided in the forecast area. The one along the Front Range (near DEN) was rather dry with a weak vertical wind shear profile, not suggestive of deep, moist convection. The air mass closer to the Kansas state border possessed substantially more moisture in the lower layers and exhibited a stronger surface wind field, both suggesting a greater likelihood of severe convection. With this initial diagnosis, the forecaster was able to begin focusing attention on the area along and east of the dryline as being most favorable for deep, moist convection.

5. The Forecast

Having made the initial diagnosis, the forecaster was now aware of what meteorological parameters would likely play a significant role in the development, or lack of development, of deep, moist convection during the next several hours. In this case, the forecaster had to evaluate the changes in the wind and stability fields above the surface that would come about as a result of the approach of the middle to upper-level, short-wave trough and upper-tropospheric jet streak. On a more local scale, an assessment of the future state of boundary layer moisture and winds needed to be made.

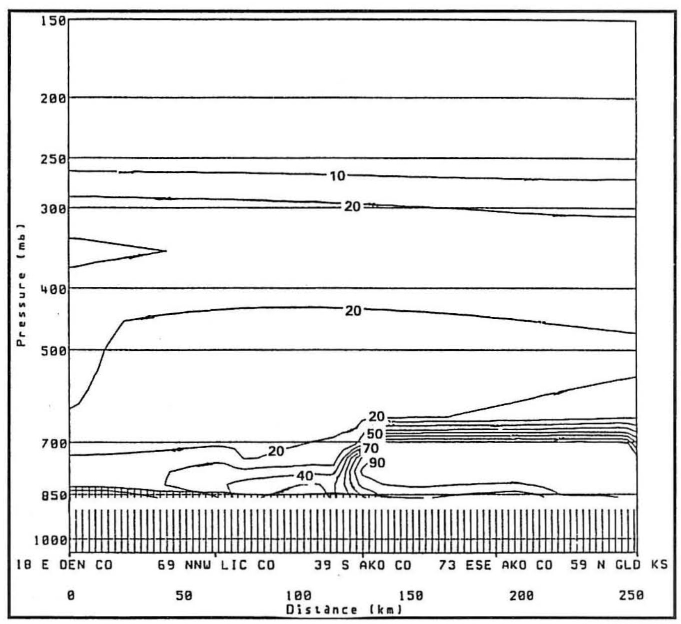

Fig. 4. 1600 UTC 21 July 1993 LAPS cross section of relative humidity (%) from DEN (left) to 59 mi north of Goodland, Kansas (GLD; right). See Fig. 5 for location of cross section.

The MAPS 12-hour forecast of 200-mb winds valid at 0000 UTC 22 July indicated that the jet streak over Utah at 1200 UTC

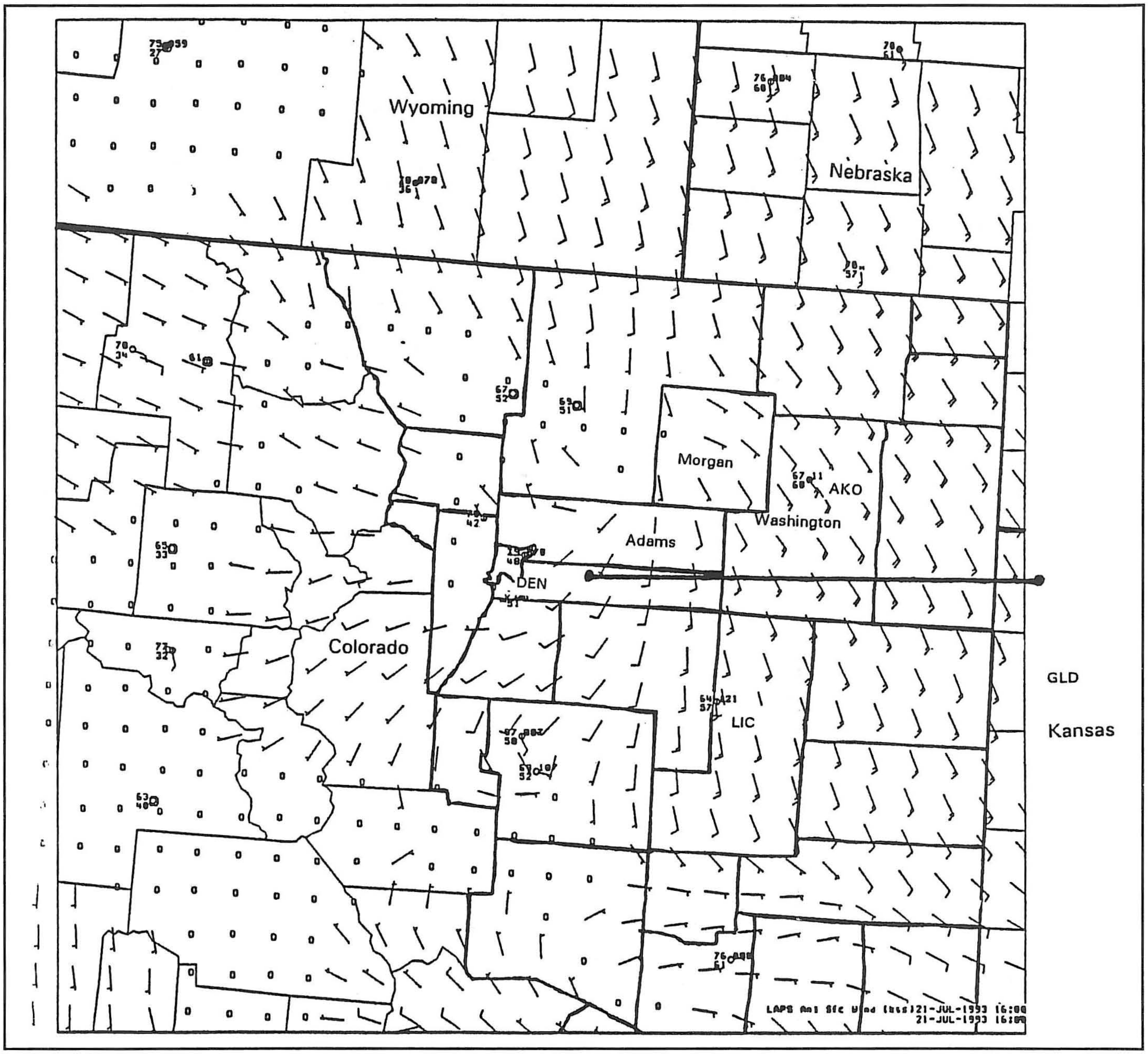

Fig. 5. 1600 UTC 21 July 1993 LAPS surface wind analysis (kt) and surface aviation observations. Winds as in Fig. 1. East-west line shows location of cross section in Fig. 4.

would progress into eastern Wyoming with speeds increasing to 95 kt (Fig. 6). This implied that mid-tropospheric winds would also be increasing over northeast Colorado during the late afternoon. At 500 mb, for example, winds analyzed over northeast Colorado at 1200 UTC at 5–10 kt were forecast to increase to 25–30 kt. While these winds are not particularly strong, they are indicative of a wind field becoming more suitable for significant convection during the day and are sufficient for severe storms in northeast Colorado according to Doswell (1980). The 700-500 mb lapse rate over northeast Colorado was initialized by MAPS at 1200 UTC at between 6 and 8 °C km^{-1}. By 0000 UTC 22 July, these values were forecast to increase to between 8 and 9 °C km^{-1} (Fig. 7), indicating destabilization. MAPS surface and 850-mb wind and pressure forecasts (not shown) indicated that a favorable pressure gradient would maintain the moderate, low-level southeast flow east of DEN.

In summary then, the MAPS forecasts suggested that conditions on the mesoscale over portions of northeast Colorado would become more favorable for strong convection as the day progressed. Consequently, the Significant Weather Outlook (Fig. 8) issued at 1730 UTC valid for that afternoon and evening specified the location of severe weather to be in and near the more moist air mass east of DEN. Note that the threat of tornadoes in this area was explicitly mentioned as a result of the expectation of supercell thunderstorms in a very unstable environment.

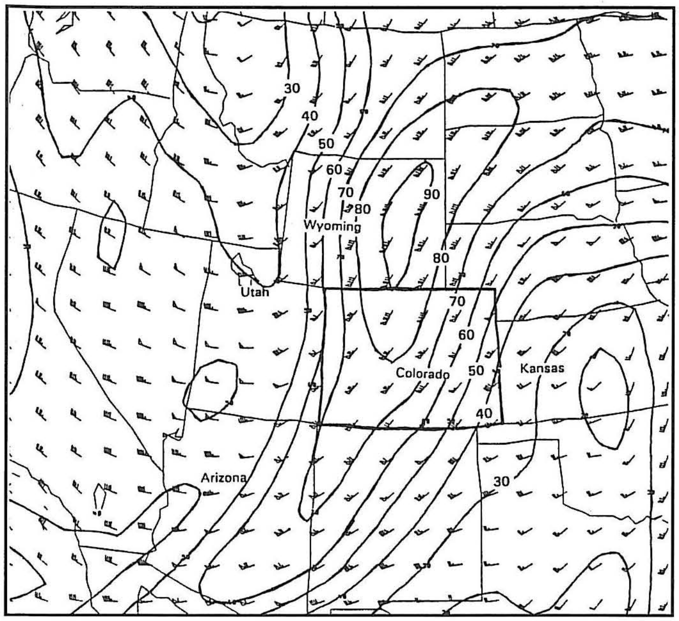

Fig. 6. As in Fig. 1, except 12-hour forecast valid 0000 UTC 22 July 1993.

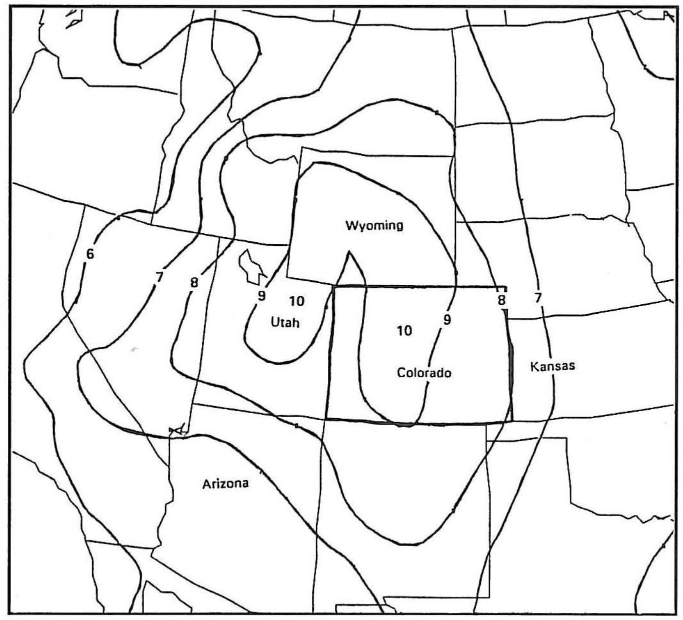

Fig. 7. As in Fig. 2, except 12-hour forecast valid 0000 UTC 22 July 1993.

SIGNIFICANT WEATHER OUTLOOK FOR NORTHEAST AND NORTH CENTRAL COLORADO
NATIONAL WEATHER SERVICE DENVER CO
1135 AM MDT WED JUL 21 1993

THIS OUTLOOK PERTAINS TO THE FOLLOWING COLORADO COUNTIES

ADAMS	DENVER	JACKSON	LOGAN	SEDGWICK	YUMA
ARAPAHOE	DOUGLAS	JEFFERSON	MORGAN	SUMMIT	
BOULDER	GILPIN	LARIMER	PARK	WASHINGTON	
CLEAR CREEK	GRAND	LAKE	PHILLIPS	WELD	

AN UPPER LEVEL STORM SYSTEM IS FORECAST TO MOVE ACROSS THE NORTHERN PORTION OF THE STATE LATE THIS AFTERNOON INTO THIS EVENING. THIS SYSTEM WILL FIRST CAUSE A FEW STORMS TO DEVELOP OVER THE HIGH COUNTRY AND THEN ALONG THE FRONT RANGE. MOISTURE IS DECREASING IN THE LOWER LEVELS OF THE ATMOSPHERE IN THOSE LOCATIONS...SO PRECIPITATION THAT OCCURS WITH THE STORMS WILL BE RATHER LIGHT. THE MAIN THREAT FROM THE STORMS THAT OCCUR OVER THE MOUNTAINS AND ALONG THE FRONT RANGE WILL BE STRONG DOWNBURST TYPE WINDS. WIND GUSTS AS HIGH AS 50 TO 60 MPH WILL BE A POSSIBILITY THROUGHOUT THE AFTERNOON.

FURTHER TO EAST...MAINLY EAST OF FORT MORGAN...LOW LEVEL MOISTURE IS QUITE A BIT MORE ABUNDANT. HOWEVER THE BIG QUESTION IN THIS AREA IS WHETHER OR NOT STORMS WILL DEVELOP. THE LOW CLOUDS AND FOG THAT COVERED MOST OF THE AREA THIS MORNING HAS LIMITED THE AMOUNT OF HEATING AND HAS ENFORCED THE CAP OR THE LID ON THE KETTLE OF BOILING WATER. THIS USUALLY INHIBITS OR DECREASES THE AMOUNT OF CONVECTION. HOWEVER...THE UPPER LEVEL STORM SYSTEM WILL HELP BREAK DOWN THE CAP AND INCREASE THE INSTABILITY WHICH WILL ALLOW STORMS TO DEVELOP BY LATE THIS AFTERNOON. BRIEF HEAVY RAINS AND LARGE HAIL WILL BE POSSIBLE. THE VERTICAL WIND PROFILE IS ALSO FAVORABLE FOR THE POSSIBILITY OF A FEW TORNADOES... MAINLY EAST OF A FORT MORGAN/DEER TRAIL LINE.

SPOTTERS MAY BE NEEDED IN THE AREAS EAST OF FORT MORGAN THIS AFTERNOON AND THIS EVENING. SPOTTERS ALONG THE FRONT RANGE MAY BE NEEDED FOR REPORTS OF STRONG WINDS.

Fig. 8. Significant Weather Outlook issued at 1730 UTC covering the period from 1800 UTC 21 July 1993 to 0600 UTC 22 July 1993.

6. The Event

The 2200 UTC LAPS analysis (Fig. 9) showed an axis of moisture flux convergence from the Nebraska-Colorado border south to near Limon (LIC). This axis had remained relatively stationary since about 1200 UTC. LAPS analyses of CAPE (Fig. 10) and CIN (Fig. 11), both calculated using surface-based parcels, showed an axis of very high instability (values between 2000 and 3200 J kg^{-1}) from northeast Morgan County through Washington County and on southward. Experience indicates these CAPE values are much higher than what typically is associated with severe weather on the Colorado eastern plains. These same areas were also still strongly capped, shown by CIN values between -150 and -300 J kg^{-1}.

Weak thunderstorms initially developed over the higher terrain southwest of DEN early in the afternoon. By 2000 UTC, the storms had moved east of DEN and were nearing the dryline and the more unstable air mass over eastern Adams County. As the storms encountered that air mass around 2200 UTC, one of them showed signs of a deep mesocyclonic circulation and a strong tilted updraft based on WSR-88D data from DEN. The other storms weakened at this point. The rotating storm produced heavy rain, intermittent large hail and two weak tornadoes between 2230 and 0030 UTC over eastern Adams county. It then moved slowly east northeast across Washington County.

At 0000 UTC, MAPS 200-mb analysis indicated the jet streak had indeed moved to eastern Wyoming as earlier forecast. Winds at 500 mb also had strengthened since 1200 UTC and were measured at 40 and 17 kt respectively at DEN and LBF. Hodographs generated from LAPS data between 0000 UTC and 0200 UTC 22 July over south central Washington County showed an increase in storm relative helicity (based on 0–3 km winds) from 65 to 144 $m^2 s^{-2}$ for a storm motion from 230 degrees at about 15 kt, indicative of an environment becoming more suitable for tornadic development (Davies-Jones 1993). Figure 12 shows the LAPS hodograph at 0200 UTC in south central Washington County. Using the actual storm motion of from 270 degrees at 12 kt as input by a forecaster and comparing 0000 UTC to 0200 UTC, storm relative helicity showed an increase from 130 $m^2 s^{-2}$ to around 200 $m^2 s^{-2}$, reaching into the range shown by Davies-Jones et al. (1990) to be sufficient for tornadoes.

A second and more important line of thunderstorms developed west of the initial group after 2000 UTC. These storms followed the same pattern of development as the earlier ones, becoming more intense as they neared the dryline. Again, one of the storms eventually became supercellular based on WSR-88D data from DEN while the others weakened. Two significant tornadoes were observed from this second storm in southwest Washington County between about 0155 and 0245 UTC. These tornadoes occurred in an environment in which storm-relative helicity had recently increased between 0000 and 0200 UTC as indicated by LAPS generated hodographs.

Fortunately, the part of Colorado which experienced the tornadoes is sparsely populated and damage was relatively limited with no injuries. One of the tornadoes from the second storm reached F3 intensity (Fujita 1971) with a 12-mile long path. The other significant tornado, also from the second storm, occurred over open rangeland and could only be rated F0 with a 6-mile long path. In addition to the tornadoes, a radar-estimated (and spotter-verified) 3–4 inches of rain fell across central Washington County from the storms. Perhaps most importantly, unlike some severe weather situations, the many warnings that were issued during this event were "expected"; i.e., the location and timing of most of the events were anticipated well in advance of their actual occurrence. This allowed

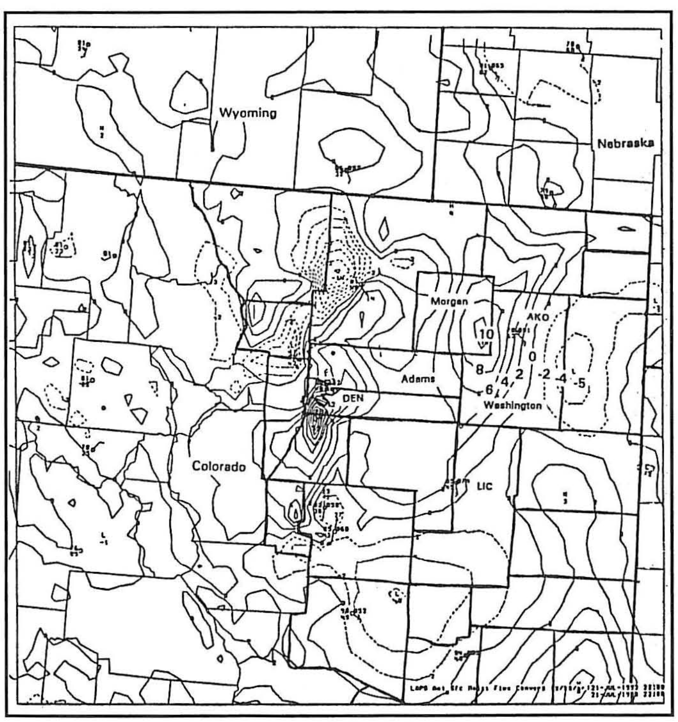

Fig. 9. LAPS 2200 UTC 21 July 1993 analysis of surface moisture flux convergence (g kg^{-1} h^{-1}).

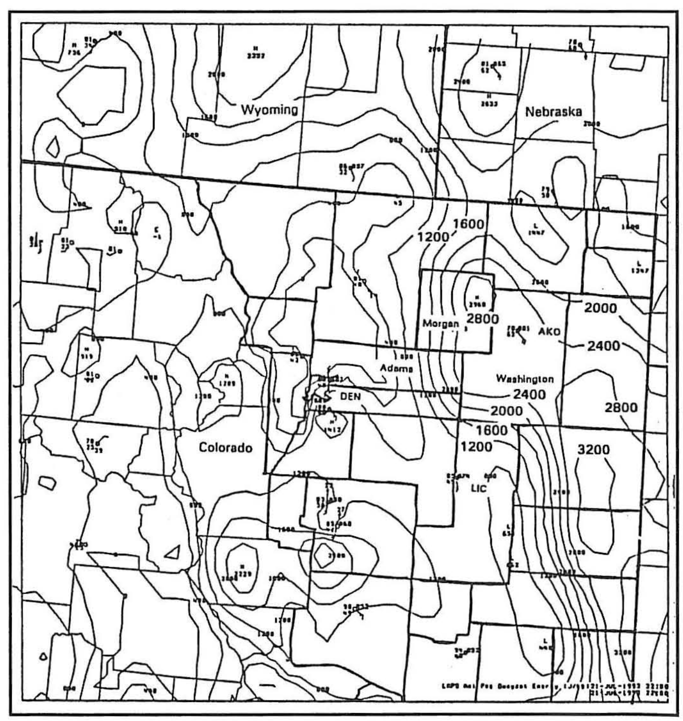

Fig. 10. LAPS 2200 UTC 21 July 1993 analysis of convective available potential energy (CAPE) (J kg^{-1}).

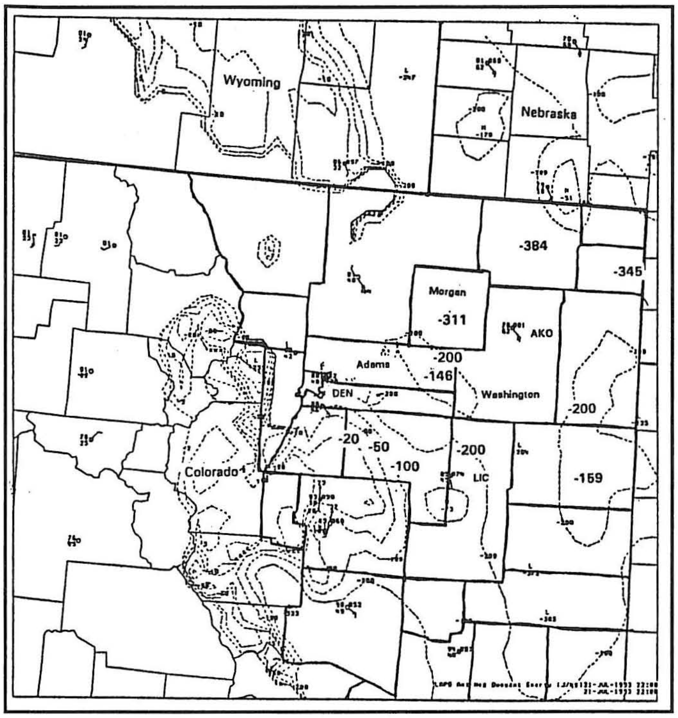

Fig. 11. LAPS 2200 UTC 21 July 1993 analysis of convective inhibition (CIN) (J kg^{-1}).

spotters to be deployed in the area prior to tornadic development. Additionally, forecasters were prepared for possible tornadic activity so that data provided by LAPS and the WSR-88D permitted the unusual intensity of the event to be conveyed to the public in warnings and statements.

7. Concluding Remarks

While not providing a detailed case study of the 21 July 1993 severe weather event, this paper has provided an overview of how the event was handled in real time during the mesoscale forecast experiment at the NWS Forecast Office at DEN. It has been shown that a logical and scientifically sound approach to forecasting using new high resolution data sets can provide a significant and practical lead time in assessing a potential severe weather event at the local office level. Having a forecaster concentrate on smaller space and time scales can result in improved short term forecasts and warnings since the forecaster can better focus on changes in the mesoscale environment.

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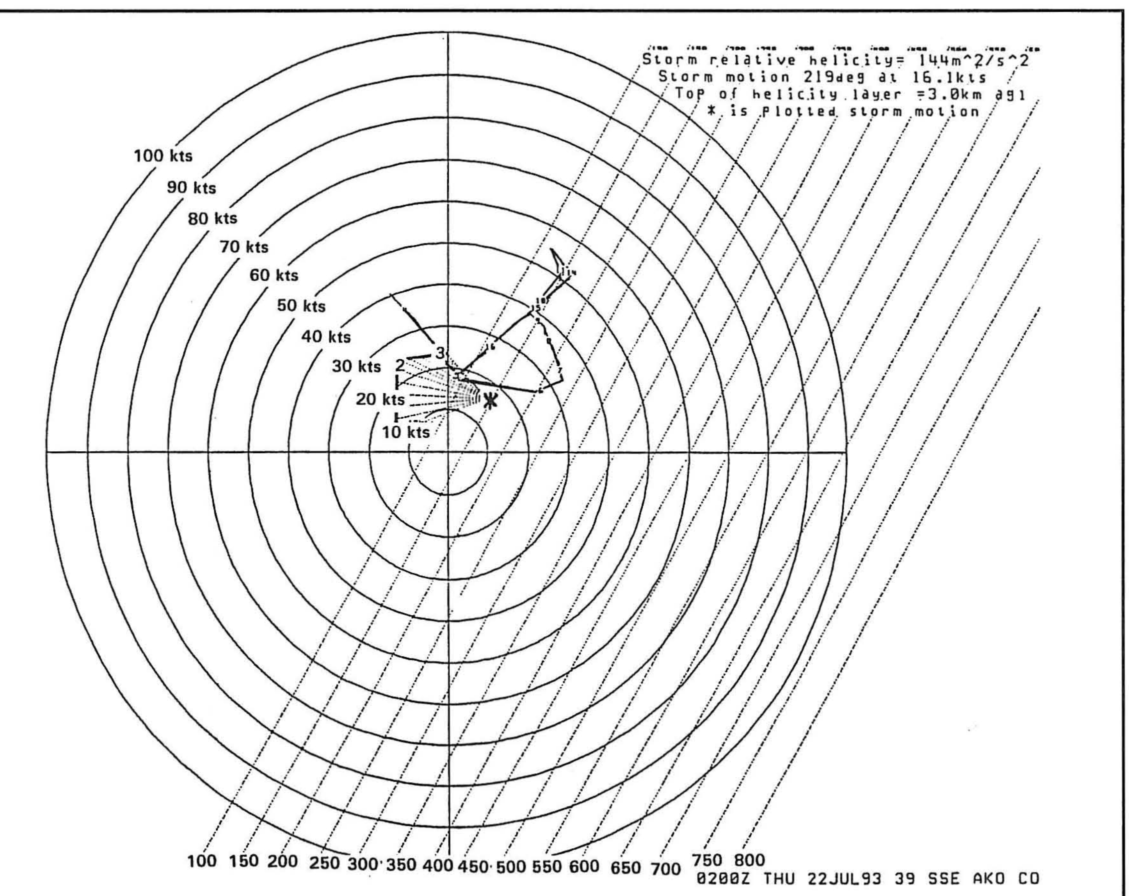

Fig. 12. LAPS 0200 UTC 22 July 1993 hodograph 39 mi south southeast of Akron (AKO). Asterisk denotes calculated storm motion based on analyzed winds. Dotted lines emanating from asterisk depict storm relative wind vectors. Straight lines running up from left to right are contours of storm relative helicity in $m^2 s^{-2}$.

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