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USE OF DUAL-DOPPLER RADAR ANALYSES IN A COMPOSITE STUDY OF A MIDLATITUDE SQUALL LINE OBSERVED DURING PRE-STORM

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1. INTRODUCTION

During the Oklahoma-Kansas Preliminary Regional Experiment for Stormscale Operational and Research Meteorology - Central Phase (PRE-STORM), see Cunning (1986), a special rawinsonde network was put into service and two 5-cm wavelength Doppler radars operated by the National Center for Atmospheric Research (NCAR) were deployed just west of Wichita, Kansas, on a 60 km NNE-SSW baseline. Coordinated sequences of Plan Position Indicator (PPI) scans with elevation angles extending from 0.2° to 58° were collected during May-June 1985 to study the structure and evolution of Mesoscale Convective Systems (MCSs). In addition, three wind profilers were used to obtain a high temporal resolution set of horizontal winds (Augustine and Zipser, 1987). A surface network of 84 automated stations spaced about 45 km apart that recorded thermodynamic, wind and precipitation data was also employed (Johnson and Hamilton, 1988).

The experimental design of PRE-STORM provides an opportunity to assimilate data from a wide variety of sources, including dual-Doppler radar scans, to produce the most thorough possible mesoscale analysis. The rawinsondes provide coverage of the wind field over an area of about 2.5 x 10^5 km^2 but with rather course resolution. The dual-Doppler analyses provides high resolution flow patterns over a roughly 200 km wide swath across the storm. The profiler and surface network are characterized by temporal and spatial resolution that allow further improvements in the analysis of the mesoscale flow patterns. A major goal of mesometeorology is to be able to assimilate such a variety of information from multiple sources into the best coherent picture of the mesoscale phenomenon under investigation. We have attempted such a combination in a composite study of the 10-11 June 1985 MCS that passed through the PRE-STORM area.

This storm was a squall line with a trailing stratiform precipitation region. Smull and Houze (1987) and Rutledge et al. (1988a) have presented the single-Doppler radar derived kinematic structure of the squall line. The latter study includes vertical velocity profiles in the stratiform region obtained from Velocity Azimuth Display (VAD) and vertically pointing techniques. Rutledge et al. (1988b) present a preliminary dual-Doppler analysis of the wind field and airborne microphysical data in the stratiform region. Johnson and Hamilton (1988) use rawinsonde, profiler, and surface mesonet data in a composite study of the dissipating stage of this storm. Biggerstaff et al. (1988) discuss the dual-Doppler derived vertical velocity structure in the convective region of this and two other MCSs observed during PRE-STORM.

In this paper, five separate dual-Doppler analyses, each 120 km x 120 km, have been combined with profiler, high frequency rawinsonde and surface mesonet data in a time-space composite study of the mature phase of the 10-11 June 1985 squall line. This analysis covers the breadth of the squall line from the environment ahead of the storm to the region just behind the trailing stratiform precipitation. Primiarily because of the inclusion of the dual-Doppler radar analyses, high spatial resolution was achieved over much of the region covered by the composite. We show that the mesoscale ascending front-to-rear relative flow at upper levels, the descending rear-to-front relative flow at mid-levels, a mesoscale region of convergence at the leading edge of the squall line and mesoscale divergence beneath the trailing stratifrom rain region were better revealed in the composite study with the inclusion of the dual-Doppler analyses than in any individual data set considered separately.

2. DATA AND METHOD OF ANALYSIS

2.1 Doppler Radar

Coordinated sets of PPI scans from the two 5-cm NCAR Doppler radars starting at 0209, 0345, 0414 and 0510 UTC were first analyzed using the method discussed by Biggerstaff et al. (1988). The radial velocity and radar reflectivity from the two radars were interpolated onto a Cartesian grid with 1.5 km horizontal spacing and 0.5 km vertical spacing. The two sets of radial velocities were combined to produce estimates of the horizontal winds. Particle fallspeeds were removed using a reflectivity weighted fallspeed estimate. Divergence was then calculated and the anelastic continuity equation was applied to determine the vertical velocity. Corrections for vertical velocity were then made to the horizontal winds from which a new estimate of divergence and vertical velocity were obtained. This procedure was repeated until the mean of the absolute value of the change in the horizontal wind components at each level from one iteration to the next was less than 0.1 m/s. Normally, four iterations were necessary for analyses containing intense convection and two or three iterations for analyses containing stratiform precipitation.

All of the scans mentioned above, except for the one at 0510 UTC, were taken by sweeping azimuthally over a 360° conical surface. This provided data for analyses on both sides of the NNW-SSE baseline (hereafter called the east and west lobes). In this study we make use of the 0209 UTC east and west lobe, the 0345 UTC east lobe, the 0414 UTC west lobe and the 0510 UTC east lobe analyses.

The orientation of the composite map of the 10-11 June 1985 storm is shown in Figure 1 along with the region covered by the dual-Doppler analyses and a typical distribution of rawinsonde and profiler data points. These positions were determined by tracking the location of the squall line's leading edge from composites of radar reflectivity from the National Weather Service (NWS) WSR-57 radars at Amarillo, Wichita, and Oklahoma City. The positive X-axis points toward 125° (toward the ESE) and is taken to be normal to the squall line. The positive Y-axis points toward the NNE and is taken to be parallel to, or along, the squall line. The half of the squall line extending into the region of negative Y will be referred to as the "southern" portion of the line, with the remainder referred to as the "northern" portion of the line.

The location and size of the convective and stratiform region (with its embedded secondary maximum of stratiform rain--the "secondary band") was determined from the composite NWS WSR-57 reflectivity radar data. During the mature and dissapting phases, this storm exhibited a well-defined transition zone. But the composite study acted to smooth out the transition zone and to enlarge the region covered by the secondary band.

The storm-relative streamline and isotach analyses were determined from the dual-Doppler derived horizontal winds by subtracting a storm motion of 18 m/s from 305° (equivalent to 18 m/s along the X-axis in the composite framework). In areas that overlapped, the analysis closest to 0330 UTC, the mean time of the composite, was used. This served to reduce the effects of evolution since, in a time-space composite study of this type, the mesoscale flows in the storm are assumed to be in a steady state.

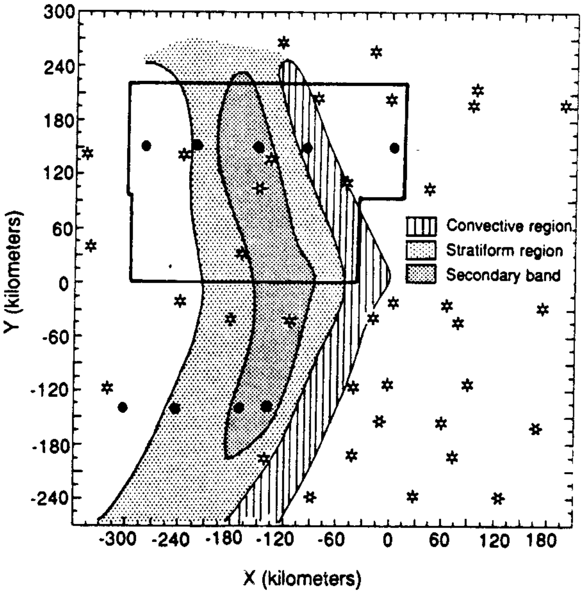

Figure 1. Composite low-level radar reflectivity structure of the 10-11 June 1985 squall line. The thick black line outlines the region of dual-Doppler coverage. The closed circles indicate profiler data points and the asterisks (*) indicate rawinsonde data points at the 800 mb level.

2.2 Rawinsonde and Profiler

The rawinsonde data were obtained from the National Severe Storms Laboratory (NSSL) after they had been edited and interpolated to 150 meter intervals. We interpolated the data to 25 mb intervals assuming that the winds varied linearly with height and that pressure varied exponentially. Data from all the rawinsonde releases between 0105 and 0600 UTC on 11 June 1985 in the PRE-STORM network were considered for use in the composite analysis. The soundings were plotted on skewT-logP diagrams and those containing large superadiabatic lapse rates or other suspect data were removed.

The location of each rawinsonde relative to the squall line was carefully determined at each pressure level, taking into account the balloon drift. Whenever two or more soundings were determined to be in virtually the same location relative to the squall line, the sounding closest to the mean analysis time was used and the others ignored.

The profiler data were obtained from the National Oceanic and Atmospheric Administration's Environmental Research Laboratory (NOAA/ERL). Vertical profiles of the horizontal winds at McPherson and Liberal, Kansas, were provided at thirty-minute intervals. Only these two of the three wind profilers were operating during the 10-11 June 1985 storm. In this study we make use of roughly every other profile of the horizontal winds. This procedure provided a set of data with resolution similiar to that of the 90 minute rawinsonde releases. It also avoided using the wind profiles at the McPherson site during periods that this profiler had bad upper level winds.

The profiler data, which were recorded at constant height levels, were interpolated to constant pressure surfaces by using the geopotential height of neighboring rawinsondes. The storm-relative horizontal winds were plotted from the profiler and rawinsonde data in the squall-line relative coordinate system. A streamline-isotach analysis using all the data sources was then performed by hand.

2.3 Surface Mesonet Stations

Data from the 84 automated surface stations were obtained from NOAA/ERL and consisted of 5 min averaged thermodynamic and wind measurements, and acculumated rainfall recorded at 5 min intervals. Time-series plots at each station for all recorded variables from 0000-0700 UTC on 11 June 1985 were constructed to check for data quality. Suspect data were removed from the data set. Afterward, the data collected from 0105-0600 UTC on 11 June 1985 were placed into the composite study by averaging all the values falling within each 15 km x 15 km grid box in the squall-line relative coordinate system. Grid boxes without data were filled and then the data were filtered to remove wavelengths less than 45 km. The storm-relative streamline-isotach plots were then constructed using standard NCAR graphics routines.

3. RESULTS

3.1 Surface Level

Ground-based dual-Doppler radar analyses do not accurately depict surface winds because of the problem of the radar horizon. However, storm-relative streamline-isotach analysis from the surface mesonet data (Fig. 2) shows front-to-rear flow throughout the entire storm with strong convergence (3×10^{-4} s^{-1}) at the leading edge of the squall line, moderate divergence (1×10^{-4} s^{-1}) over the broad trailing stratiform region and moderate convergence at the back edge of the surface precipitation region into a wake low that was present in the surface pressure analysis (not shown). These features were also noted in the surface analysis of Johnson and Hamilton (1988).

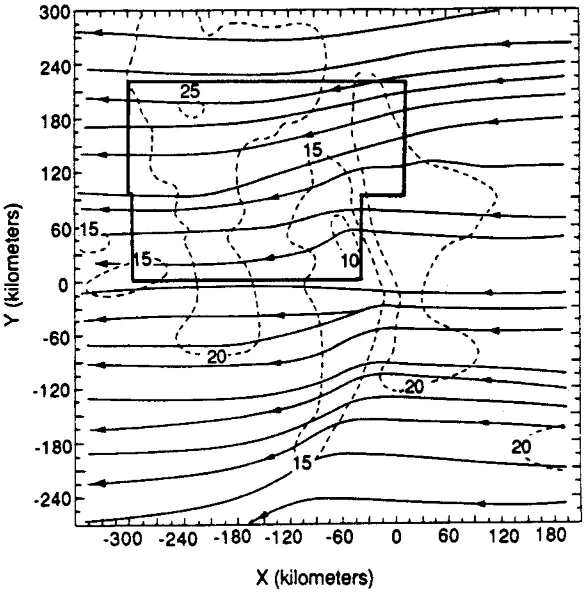

Figure 2. The surface level streamline-isotach analysis. Streamlines are solid black lines with arrowheads indicating the direction of the flow. Isotachs, every 5 m s^{-1}, are dashed. The thick black line outlines the region of dual-Doppler coverage.

3.2 The 800 mb Level

The 800 mb streamline-isotach field (Fig. 3) shows that the storm-relative flow ahead of the squall line was all directed from front to rear with fairly uniform speeds. However, the relative flow through the convective and stratiform region was rather complex.

The isotach field shows that the wind speed increased as the relative flow entered the leading edge of the convective line. This structure was also noted by Smull and Houze (1987) and may have been partially the result of the air accelerating as it approached the mesolow in the convective region, as discussed by LeMone (1983) and seen in the model results of Fovell and Ogura (1988), and/or a mesolow beneath the trailing anvil cloud as seen in the model results of Brown (1979). Immediately behind the convective line the relative flow was directed from the rear to the front of the system. Thus, a sharp zone of convergence was found at the back of the convective region. This rear-to-front current extended from the back of the secondary band (X ~ -165) to the back of the convective line over most of the storm at this level. Without the five 120 km x 120 km dual-Doppler analyses the along-line horizontal extent of this feature could not have been resolved. The radar data also show continous streamlines of system-relative front-to-rear flow in the extreme northern portion of the squall line. As a result, the streamline analysis in this region exhibits cyclonic curvature. A closed mesolow, possibly of the type discussed by LeMone(1983), in the geopotential height field (not shown) was located in this region. The unbalanced flow around this low could not have been as clearly depicted without the inclusion of the Doppler analyses. Furthermore, the convergence at the leading edge of the convective region in the northern portion of the squall line would not have been as strong if the composite study used only the rawinsonde and profiler data. Thus, the inclusion of the dual-Doppler radar analyses was important in accurately depicting the horizontal extent and strength of the mesoscale flows at this level.

Toward the back of the storm, in the rearward part of the stratiform region (X < -195), front-to-rear divergent relative flow was found. It extended from the rearward portion of the stratiform area to beyond the left side of the analysis domain.

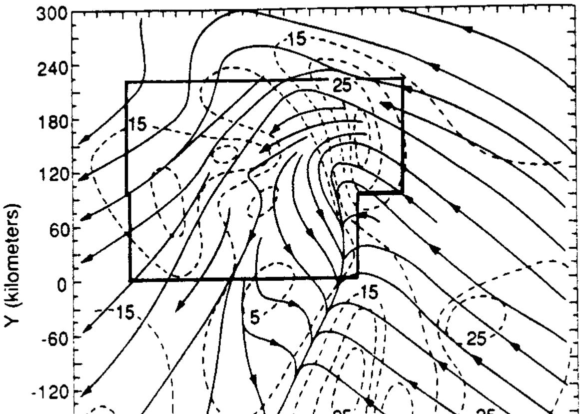

Figure 3. As in Fig. 2 except for the 800 mb level.

3.3 The 600 mb Level

Similiar to the 800 mb level, the relative flow ahead of the squall line at the 600 mb level (Fig.4) was everywhere front-to-rear and the flow through the convective and stratiform regions was again very complex. As the front-to-rear relative flow approached the leading line of convection, the windspeeds increased just as they did at 800 mb. At this level, however, the front-to-rear flow extended further to the rear in the southern half of the squall line than in the northern half. The region of weak wind speeds behind the convective line, which established strong convergence in that area, was resolved only with the dual-Doppler data.

The streamlines turn from front-to-rear to be directed more in the along-line direction in the stratiform rain region. The apparent deformation field (and its associated "northward" along-line flow) in the stratiform region over the secondary band (-150 < X < -105, 0 < Y < 75) would not have been seen using just the rawinsonde and profiler data. Toward the back of the stratiform rain region the along-line airflow decreased and the rear-to-front flow increased, especially in the northern portion of the storm. The rear inflow current was well defined in the northern half of the squall line and extended from about 60 km behind the stratiform region to the middle of the stratiform region. But in the southern portion of the squall line, there was very little rear-to-front flow. Most of the relative airflow at this level in this half of the storm was in the along-line direction. The location and strength of the rear inflow at this level would not have been well resolved without the dual-Doppler data. The simplistic nature of the mesoscale flow pattern in the southern portion of the squall line at this level may be a direct result of not having high resolution data in that area.

The inclusion of the dual-Doppler analyses in the northern portion of the squall line shows that there was no long, sharp line of convergence in the stratiform region. Rather, there was a broad region of convergence centered over the region of the secondary band in the stratiform region. Another feature that was only evident after including the Doppler radar analyses was the dual nature of the rear-to-front flow in the central portion of the squall line.

At the back of the trailing stratiform region (-270 < X < -180, y ~ 30), the large-scale rear inflow current already discussed was observed. But another, apparently separate, rear inflow current was observed in the back of the

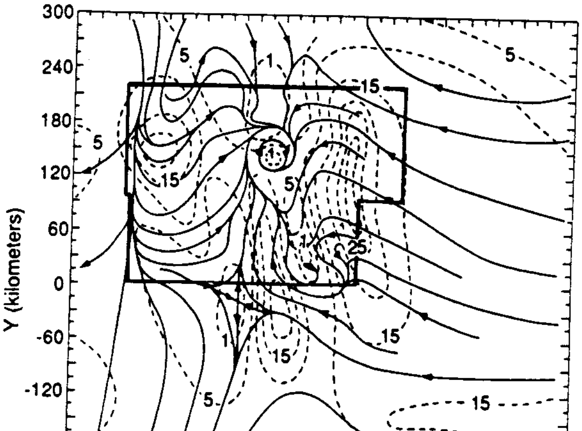

Figure 4. As in Fig. 2 except for the 600 mb level. Also, the 1 m s^{-1} isotach is included.

convective region (-90 < X < -45, y ~ 30). Both of these rear-to-front flows were associated with apparently separate, closed mesolows in the geopotential height field (not shown). This supports the notion that the rear-to-front flow might be a consequence of two separate processes that generate low pressure areas within the MCS (Smull and Houze, 1987).

3.4 The 300 mb Level

The 300 mb relative-wind streamline-isotach analysis (Fig. 5) shows that front-to-rear flow extended throughout the entire system at upper levels. Strong divergence out of the convective region and moderate divergence throughout the stratiform region was evident, even without the dual-Doppler analyses. But the observed divergence at this level would have been weaker without the inclusion of the dual-Doppler analyses. The minimum in the isotach field at the leading edge of the northern portion of the convective line, which created the large gradient of windspeed across the convective region, was observed solely from the Doppler radar data.

Furthermore, the dual-Doppler derived streamline-isotach analysis in this region shows evidence of some convergence ahead of the convective line. This convergence fed a mesoscale upper-level downdraft (not shown here, but evident in vertical cross sections through the dual-Doppler analysis in that region) that compensated for a portion of the upward mass flux in the nearby convective region. The implied subsidence evidently warmed the atmosphere through adiabatic compression and resulted in a pre-squall mesolow. The mesolow was observed in the pressure analysis from the composited surface mesonet data in this region of the storm. Johnson and Hamilton (1988) also found a surface mesolow ahead of this squall line observed at a later time.

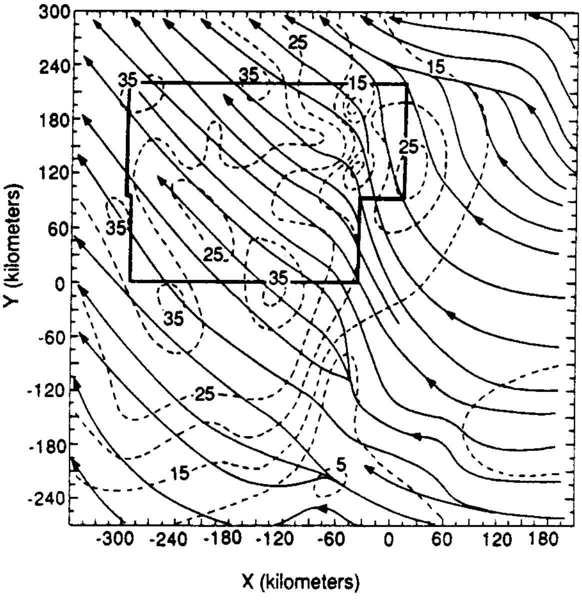

Figure 5. As in Fig. 2 except for the 300 mb level.

4. CONCLUSIONS

This study marks the first time that dual-Doppler analyses over such a large mesoscale time and space domain have been combined with rawinsonde, profiler and surface mesonet data in a composite study of the kinematic structure of a Mesoscale Convective System. The use of a series of dual-Doppler analyses in this study of the mature stage of a midlatitude squall line with a trailing stratifrom region was important in accurately depicting the strength and extent of the system-relative mesoscale-flow features through the storm. The complex structure of the rear-inflow current at low and mid levels and its relationship to a weakly organized mesolow in the trailing stratiform region were better revealed. Additionally, the increase in speed of the front-to-rear flow at low levels where it entered the convective region and the strength of the composite divergence field at all levels appeared stronger when the high resolution Doppler data were included.

This study illustrates the feasibility of assimilating mesoscale data from a variety of sources (Doppler radar, profiler, surface mesonet, and soundings) to obtain the most complete and accurate representation of the storm's circulation. Such techniques will be crucial to the success of the STORM program and in future operational forecasting and analysis on the mesoscale.

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