The Oklahoma Squall Line of 19 May 1977. Part I: A Multiple Doppler Analysis of Convective and Stratiform Structure

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ABSTRACT

On 19 May 1977, a severe squall line formed and moved through the National Severe Storms Laboratory observing network in Oklahoma, producing heavy rain, hail, strong winds, and tornadoes. The squall line is examined at two times: 1434 and 1502 CST. Doppler analysis of part of the squall line reveals four convective cells in the line, developing cells ahead of the line, a trailing precipitation region, and a convective rainband at the western edge of the system. The updrafts within the convective cells on the leading edge tilt westward in the lower levels and eastward near the tropopause. Convective updrafts and downdrafts are fed by low-level air entering the squall line from the front. Surface network analysis and gust front penetration by an instrumented aircraft indicated strong convergence along the leading edge of one of the stronger cells in the line. Horizontal, line-relative flow perpendicular to the squall line and within the trailing precipitation area is from east to west (front to back) at all levels, weakening with height. An exception to this is an area of weak (<3 m s⁻¹) rear inflow into the stratiform precipitation region in the midlevels. Flow parallel to the squall line is stronger, in general, than the perpendicular flow. A composite rawinsonde analysis shows ascending motion within the troposphere over most of the squall line region. A conceptual model is developed for 19 May 1977 and is compared to conceptual models of tropical squall lines and of the 22 May 1976 Oklahoma squall line.

1. Introduction

a. General structure of midlatitude and tropical squall lines

Conceptual models of midlatitude squall lines (Newton, 1950) suggest they form in a convectively unstable environment characterized by strong vertical shear of the horizontal wind. Vertical transport of stronger, upper-level momentum towards the surface and weaker, lower-level momentum upwards results in convergence near the surface and divergence aloft on the propagation side of the line. This configuration continuously reinforces the low-level updraft and allows squall lines to persist for hours. Evaporative cooling of dry, midlevel air entrained into the system and water loading serve to support convective downdrafts. A midlatitude squall line has intense convection along the leading edge of the system that may or may not be followed by an area of mesoscale, light precipitation.

In some cases, convective cells ahead of the line may merge with the line itself, aiding in system maintenance and propagation.

Observations (Houze, 1977) show tropical squall lines are composed of three regions: convective updrafts, convective downdrafts, and a trailing, mesoscale area of precipitation characterized by mesoscale, unsaturated downdrafts in the low levels (Zipser, 1969). Zipser (1977) proposed that the mesoscale downdraft is forced by negative buoyancy created by evaporation of water and ice from the upper levels of the trailing precipitation region. Numerical results of Brown (1979), using a time-dependent, hydrostatic model, support this explanation. Frequently, a radar bright band is a prominent feature of the trailing precipitation region. Leary and Houze (1979) suggest that mesoscale ascent above the bright band is the probable forcing mechanism for the production of precipitation within the trailing precipitation region. Srivastava et al. (1986) used an extended VAD (velocity–azimuth display) technique and Doppler analysis to show that the stratiform region of an Illinois squall line has weak ascending motion (<10 cm s⁻¹) below 1 km, descent (25 cm s⁻¹ maximum) between 1 and 5 km, and ascent (35 cm s⁻¹ maximum) from 6 km to cloud top. The vertical motions above 1 km substantiate previous hy-
potheses on motions within the stratiform region. The authors could not explain the low-level ascent, but both analysis techniques produced similar results.

Zipser and Matejka (1982) and Smull and Houze (1985) compare midlatitude squall lines to tropical squall lines. These studies indicate the following differences between the two types of systems: different directions for vertical wind shear (westerly shear for midlatitudes and easterly for the tropics), greater likelihood of severe weather with midlatitude systems (more intense circulations), a leading anvil produced by divergent flow at the tropopause in midlatitude systems (although a tropical case with a leading anvil is reported in Houze and Rappaport, 1984), and different reflectivity structures (tropical squall lines have peak reflectivity values near the surface while midlatitude systems have peak values aloft).

b. The 19 May 1977 squall line

In this study, a midlatitude squall line is examined using multiple Doppler radar analyses, a rawinsonde analysis, surface data, and data from an instrumented aircraft. The squall line formed in western Oklahoma on 19 May 1977 and moved across the National Severe Storms Laboratory (NSSL) observing network for the 1977 Spring Program. Severe weather events accompanying this system included strong winds, heavy rain, hail, and tornadoes.

Multiple Doppler analyses are the primary tools used to examine the kinematic and reflectivity structures in the convective and stratiform regions of the squall line at two times. These analyses reveal that the squall system is composed of four regions: growing convective cells ahead of the line that merge with the mature convective region, the mature convective region, a stratiform region of light precipitation, and a convective rainband at the western edge of the system. Datasets from the surface network, an instrumented aircraft, and a small rawinsonde network augment the Doppler analyses. A conceptual model of this squall line is developed from all observations. Comparisons are made between this squall line, tropical squall lines, and another midlatitude squall line. A companion paper (Hane et al., 1987) continues the analysis of this squall line by examining several mechanisms responsible for maintaining the region of mature convection.

2. Data systems and analysis techniques

a. Multiple Doppler analyses

Four Doppler radars participated in the NSSL 1977 Spring Program (Fig. 1). The Norman (NOR), Cimarron (CIM), and University of Chicago/Illinois State Water Survey (CHILL) Doppler radars operate at ~10 cm wavelength while the National Center for Atmospheric Research (NCAR) CP-4 Doppler radar operates at ~5 cm.

Doppler radar data are analyzed at 1434 and 1502 CST. Data are edited before interpolation to remove errors caused by ground clutter, second trip echoes, sidelobes, and low signal-to-noise ratio (Oye and Carbone, 1981). Because of the large horizontal extent of the squall line and limited computer memory, analyses are performed over two overlapping grids that are recombined. Grid points along the boundary between the two halves are not included. Data are gridded using a Cressman (1959) distance-dependent weighting function over a spherical influence volume with a 1 or 1.5 km radius depending on radar distance from the grid. Wind fields are derived using a dual-Doppler analysis technique that allows data from more than two radars to be included, resulting in an overdetermined system of equations. Cartesian components of the wind are computed in a least-squares sense after an initial estimate for vertical velocity is applied and the hydrometeor fallspeed is estimated from radar reflectivity (Joss and Waldvogel, 1970). Vertical velocity is computed from downward integration of the anelastic equation of continuity for the 1434 analysis and from upward integration for 1502 (all times are CST). Convergence to a final solution is achieved by iteration. At 1434, all wind components are variationally adjusted using the vertically integrated mass flux form of the equation of continuity as a strong constraint. The Appendix contains details of the overdetermined dual-Doppler analysis procedure and error variance calculations.

The analysis domains for both time periods include a volume with dimensions 155 km perpendicular to the leading edge of the squall line (east–west), 60 km parallel to the squall line (north–south), and 14 km
deep. Horizontal and vertical grid spacings are 1 km. The 1434 analysis contains data from four Doppler radars. At 1502, NOR did not collect data and the three radars did not scan to the top of the mature cells. Also, elevation steps varied within the scans at 1502, leading to data gaps and analysis holes. For these reasons, the analysis at the second time is not as complete as the first, upward integration must be used to obtain vertical velocity estimates, and wind components cannot be variationally adjusted.

b. Surface networks

In 1977, the NSSL mesonet and the NCAR Portable Automated Mesonet (PAM) (Brock and Govind, 1977) were combined to form a single surface network (Fig. 1). The NSSL mesonet consists of 25 stations while the PAM network has 15 stations, creating a nested grid within the NSSL mesonet. Average spacing between all stations in the network is \( \sim 25 \) km with a spacing of \( \sim 10 \) km in the nested grid.

c. Rawinsonde network

The rawinsonde network consisted of four stations: Elmore City (EMC), Radio Tower KTVY (TVY), Fort Sill (FSI), and Clinton–Sherman (CSM) (Fig. 1). Each station made two balloon releases during the time of interest (roughly two hours apart), so that a total of eight soundings are used in the analysis. Times for sounding release are 1346 and 1607 at FSI, 1434 and 1600 at EMC, 1435 and 1558 at TVY, and 1430 and 1616 at CSM. To analyze the rawinsonde network data, a compositing technique is used. Assuming steady-state conditions exist in the mesoscale environment of the squall line, station positions at the surface are adjusted relative to the leading edge of the squall line (defined as the 20 dBZ contour). Squall line motion is removed from wind observations. Balloon positions are plotted relative to the leading edge of the line after adjusting for displacement in time and space from the release time and location. Soundings were not taken in mature convection or 30–100 km west of the leading edge of the line. The 1558 TVY sounding was terminated near 5 km, creating a data gap in the upper levels of the analysis. Results from the analysis must be examined with these limitations in mind. Vertical velocity is computed by downward integration of the mass continuity equation from a boundary condition of \( w = 0 \) m s\(^{-1}\) at 16 km.

d. Instrumented aircraft

The instrumented NCAR Queen Air aircraft participated in the 1977 Spring Program. The aircraft records temperature, dewpoint temperature, pressure, wind speed and direction as well as other atmospheric parameters at 1 s intervals. It has an inertial navigation system for calculating ground-relative position and aircraft movement.

From 1438 to 1516, the Queen Air flew perpendicular legs at increasing altitudes south of preline convective cells and ahead of the squall line. The purpose of this flight pattern was to obtain a vertical cross section of variable fields immediately ahead of the convection in the line. Wind data collected by the aircraft and wind data from the 1434 Doppler analysis are combined (as described in section 7) to better determine horizontal and vertical variations in the low-level inflow region. To lessen the effect of high-frequency variations, aircraft winds are averaged over 30 s intervals. Doppler-derived fields are averaged along the \( y \)-axis over a 7 km region bracketing the aircraft’s north–south position (from \( y = 0 \) to \( \sim 7 \) km) to lessen the differences caused by selecting one particular east–west vertical cross section.

4. Synoptic conditions on 19 May 1977

At 0600 CST on 19 May 1977, a cold front extended from a synoptic low in central North Dakota southwestward to eastern New Mexico. Mesoscale lows were in eastern New Mexico and northern Kansas along the front. At 850 mb, a warm-core trough was along the lee of the Rocky Mountains with a dry-air intrusion in southwestern Texas and southeastern New Mexico. Southerly surface winds and a low-level jet were advecting moisture from the Gulf of Mexico into Oklahoma through a deep layer.

At 500 mb, a trough was west of Oklahoma with lowest heights over Montana. The 500 mb thermal trough was north of Oklahoma, leaving the area of interest in warm advection. Two 500 mb short waves moved across Oklahoma. The first contributed to the development of predawn thunderstorms in the Texas Panhandle while the second, more intense disturbance advected into western Oklahoma during the early afternoon. The low-level jet and strong westerly winds in the middle levels created a vertically sheared environment favorable for convective development.

The 1400 surface map (Fig. 2) shows the synoptic cold front is in the Texas Panhandle, west of the developing squall line. Also, a mesoscale low is in western Texas with a dryline extending southward and a trough extending towards the east-northeast. A mesohigh, resulting from cool convective outflow, is east of the cold front. The leading edge of the squall line is indicated by the dashed line. Winds are southeasterly and dewpoint temperatures are a maximum ahead of the mesohigh.

The 1434 Elmore City sounding (Fig. 3), taken in the undisturbed, environmental air ahead of the squall line and at the same time as data collection leading to the first Doppler analysis, shows the air mass is convectively unstable. The lifted index is \(-8\), based on the mean potential temperature of 300 K and mixing ratio
of 13.8 g kg\(^{-1}\) within the lowest 150 mb. A deep, low-level moist layer is present with rapid drying above the base of a 3–4 K inversion at 680 mb. The freezing level is at ~4 km AGL. Winds are southerly from the surface to 450 mb, veer to southwesterly and increase to 40 m s\(^{-1}\) at 350 mb, then decrease.

5. Convective history of the 19 May 1977 squall line

To trace the evolution of the 19 May 1977 squall line, a series of photographs of the NSSL WSR-57 Plan Position Indicator (PPI) radar scope are presented (Fig. 4). By 1023, the predawn thunderstorms in the Texas Panhandle have nearly dissipated, leaving an area of first and second-level echoes (≤24 dBZ\(_0\)). New, third-level (≤34 dBZ\(_0\)) storms are forming near the southern edge of the old storms. By 1230, convective development is occurring both northeast and southwest of the older echoes. At 1319 (not shown), six large cells are oriented nearly north-south in a broken line.

By 1434 (Fig. 4c), the convective cells have expanded and areas between cells filled with precipitation, forming the ~300 km long squall line. From the first radar echo, consolidation of individual cells into the squall line took ~6 hours. The leading edge (defined as the lower limit of second-level echo or 24 dBZ\(_0\)) of the system is oriented north-south. Largest cells (fifth-level echo) are at the eastern edge of the squall line and are ~40 km across. Widespread second and third-level echo trails the mature convection for 60–70 km. This case appears to most closely resemble “broken-line formation” (Bluestein and Jain, 1985), where discrete cells in a line gradually expand and fill intervening gaps, forming a solid squall line. By 1502, the squall line has propagated eastward at 10 m s\(^{-1}\) to the location shown in Fig. 4d. Doppler analyses of the squall line wind and reflectivity fields are completed at 1434 and 1502, corresponding to Figs. 4c and 4d.

Cells within the line produced damaging winds with a reported maximum of 27 m s\(^{-1}\), maximum rain amounts of 18 cm in 2 h, hail 0.5 to 1 cm in diameter with severe hail damage along a 10–15 km path in southwestern Oklahoma, and small tornadoes at 1630, 1723, 1736 and 2130. Convective cells within the squall line moved from 207° at 10 m s\(^{-1}\), nearly parallel to the low-level shear vector in the 1434 EMC sounding. Line motion of 10 m s\(^{-1}\) from 270° is approximately along the midlevel shear vector. Because nearly half the eastward propagation of the squall line is due to convective cell motion, a nearly equal amount of propagation must be due to the development of new
Fig. 4. Photographs of the NSSL WSR-57 PPI radar scope on 19 May 1977. Range marks in (a) are at 100 km and in (b), (c) and (d) are at 40 km. Contours are shaded as follows: dim is 20 to 23 dBZ, bright is 24 to 33 dBZ, cancel is 34 to 45 dBZ, dim is 46 to 57 dBZ, and bright is 58 to 69 dBZ. Times shown are (a) 1023, (b) 1230, (c) 1434, and (d) 1502 CST. Boxes represent the location of the Doppler analyses. Cells within the mature convective region are labeled.
convection on the eastern edge, either continuously or discretely. The mean tropospheric wind ahead of the squall line is 21 m s\(^{-1}\) from 202°, as determined from four soundings.

6. Rawinsonde analysis of 19 May 1977

Results from the rawinsonde analysis (Fig. 5) described in section 2c reveal the east–west component of the wind is from front to back and 6 km deep ahead of the line. Within the line, easterly flow (< -5 m s\(^{-1}\)) is 6 km deep to 50 km behind the leading edge and is <2 km deep from that point westward. In the low levels, maximum easterly winds of -15 m s\(^{-1}\) are found near the leading edge of the squall line below 1 km. A divergent pattern is seen above 6 km. Placement and strength of horizontal gradients is uncertain due to the coarse spatial and temporal resolution.

A large area of mesoscale ascent occurs behind the leading edge of the line (Fig. 5b) with maximum ascent of 70 cm s\(^{-1}\) between 5 and 7 km within the stratiform precipitation region. These results suggest precipitation may be produced in the mid- and upper-levels of the stratiform rain area of the system, as proposed by Leary and Houze (1979). Below 2 km and near -120 km a small area of weak descent can be seen, consistent with Zipser's (1977) suggestion that mesoscale downdrafts occur in this region. Sampling deficiencies within the stratiform region may not allow observation of the total area of the mesoscale downdrafts.

7. Structure of the 19 May 1977 squall line

a. Horizontal structure

Based upon the two Doppler analyses, the squall system is divided into four regions, as indicated in Figs. 6 and 11. The preline convective region consists of developing cells ahead of the squall line that gradually merge with the mature convective cells along the eastern edge of the squall system. Preline cells are labeled E, E' and E". The mature convective region contains mature cells that have vigorous updrafts and downdrafts. Cell A is the largest cell and has the strongest updrafts among those cells labeled A, B, C and D. West of the mature convective region and within the stratiform region is a relative maximum in reflectivity ≥25 dBZ, labeled F. This feature extends to ~4 km AGL and has a weak bright band. The fourth region is the postline rainband located at the western edge of the squall system, labeled G.

Because of the large horizontal extent of the squall line, it is not possible to show the detailed flow characteristics of the entire line. Detailed features of cell A

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**Fig. 5.** Analyzed rawinsonde fields in vertical cross section on 19 May 1977. Distance is computed relative to the leading edge of the squall line (x = 0 km). Fields shown are (a) line-relative, east–west wind component (m s\(^{-1}\)) and (b) vertical velocity (cm s\(^{-1}\)). The four regions of the squall line are indicated.
are shown within areas denoted by boxes in Figs. 6 and 11. Squall line motion (270° at 10 m s⁻¹) is subtracted from horizontal flow so that Doppler-derived winds are line-relative in the figures that follow.

Figure 6a shows the 1434 Doppler-derived reflectivity field at the lowest level (150 m AGL), and identifies the features discussed above. Because terrain height above mean sea level increases to the west in Oklahoma, the height of the lowest radar beams above the ground remains nearly constant within the domain. Easterly inflow converges with the outflow from cell A (Fig. 7) at the gust front, defined by the band of cyclonic shear and convergence extending southeastward from cell A through the reflectivity notch (−42, 5). The major updraft is above the reflectivity notch (Fig. 9b). A relative maximum of reflectivity extends northeastward from cell A. Reflectivity data from the WSR-57 radar reveal this northeastward extension is a preline echo in the process of merging with the line. Ahead of cell A, the preline convective cells E and E' contain easterly flow, showing no evidence of low-level, divergent outflow. Single Doppler observations from NOR as low as 30 m AGL also show no evidence of divergent outflow within the preline cells. Flow into cell B is southeasterly instead of easterly as in cell A; no preline convective cells precede cell B. An area of cyclonic shear exists along the boundary between the inflow and outflow of cell B; however, no reflectivity notch is present.

Fig. 6. The 19 May 1977 Doppler-derived fields at the lowest level (150 m) at 1434 CST. Fields shown are (a) reflectivity (dBZ) and (b) line-relative, horizontal winds (m s⁻¹) and reflectivity (dBZ). Scale vectors for the winds is at the upper right. Every third vector is plotted in each direction. Reflectivity is contoured every 10 dBZ. Locations of vertical cross sections shown in Figs. 16, 19–21 are indicated in (a) and important features are labeled. The dash-dot-dot line is the gust front positions. Distances on the axes are north (vertical) and east (horizontal) of Norman. Box indicates location of Fig. 7.
Within the stratiform precipitation area, F, and the postline rainband, G, line-relative winds are easterly to northeasterly. In general, near-surface flow is from front to back in the observed area.

The 1434 surface analysis (Fig. 8) shows a southwest–northeast-oriented trough containing a nearly circular area of low pressure along the gust front and a cyclonic circulation in the winds. This mesolow is positioned near the location of the reflectivity notch of cell A. Highest pressure is recorded beneath the maximum reflectivity of cell A. Individual surface stations show the gust front is characterized by a wind shift from southeasterly to westerly (ground relative), a pressure increase of ~1 mb, and a temperature decrease of ~5 K.

Horizontal divergence is calculated at various times using surface data. At 1415, strongest convergence is along the gust front (see Hane et al., 1987, Fig. 10a). However, an area of weaker convergence extends eastward ahead of the gust front. WSR-57 PPI data reveal several preline cells within this convergence area. Possible forcing mechanisms for preline convection are examined in more detail in the accompanying paper (Hane et al., 1987). At 1434, the surface analysis reveals that the maximum convergence zone (see Hane et al., 1987, Fig. 10b) is southeast of the reflectivity notch (Fig. 7) and along the gust front position.

At 5 km (Fig. 9), horizontal flow is southerly to southeasterly ahead of the line. Within the convective region, cyclonic curvature of the horizontal winds exists within the updrafts of cells A, B and C, while downdrafts exist in areas between the three cells. Two maxima in the reflectivity field of cell A indicate the presence of smaller cells rather than one large cell. Since conceptual models of tropical squall lines (Houze, 1977; Gamache and Houze, 1983) show older convective cells move to the rear of the system, the western cell is interpreted as the older cell. Within the trailing rain region and the rainband G, flow is southerly. Region F is not identifiable at this altitude.

At 10 km (Fig. 10), the lower portion of the divergent area at the top of cell A can be seen. The two reflectivity maxima seen at 5 km are identifiable and a third (very likely the oldest) maximum can be seen. Cells B and C encompass only small areas at this altitude. Within the trailing precipitation area, storm-relative winds are southerly. Region G does not extend to this altitude.

At 1502, the analysis domain has been moved 10 km east from the 1434 location, but is otherwise the same (Fig. 11). Near the surface (150 m AGL), the preline convective cell E has completely merged with the line and cell E' is in the merger process. A new preline convective cell containing easterly flow has moved into the analysis domain from the south and is labeled E' . Movement of all preline cells is determined by examination of the WSR-57 PPI data, and is treated in greater detail in an accompanying paper (Hane et al., 1987). Southeasterly flow into cell A has intensified since 1434 (Fig. 12) while the area of 45 dBZ has decreased and the reflectivity notch has disappeared. Cell B is out of the grid domain and easterly flow between cells A and B has intensified. Cell C contains easterly to northeasterly flow, and as another cell, D, which has moved into the analysis domain from the south. Within regions F and G, winds are easterly and north-easterly, respectively.

The 1502 surface analysis (Fig. 13) shows that the mesolow has weakened, leaving a southwest–northeast oriented trough. A new low has formed south of the trough near (~45, ~15). This area is outside the area covered by the Doppler analysis; however, the WSR-
57 PPI data indicate a heavy precipitation core near that area. Highest pressure behind the gust front is oriented approximately north-south. The strong thermal gradient associated with cell A has propagated to the northeast, while thermal gradients have weakened along the southern half of the gust front.

The general features contained within the upper levels of the squall line have not changed remarkably since 1434. At 4 km (Fig. 14), wind speeds within the mature convective region have increased since the previous analysis time, while wind directions have remained nearly the same. Within cell A, the forward updraft has weakened, has an irregular shape, and is surrounded by downdrafts. A large area of downdraft has formed between cells A and B. The updrafts associated with cell C are weak and disorganized. West of the main line, southeasterly flow from the convective cells is confluent with the southerly flow within regions F and G.

b. Vertical structure

A sounding derived from research aircraft data is plotted with the 1434 EMC sounding (Fig. 15) to compare the temperature, moisture, and wind profiles in the near and far (∼70 km east) environments of the squall line. The near environment is ∼0.5 K warmer between 810 and 880 mb. Air from 750 to 670 mb is 0.5 to 1.0 K cooler near the line. The base of the inversion has risen to 690 mb compared to 705 mb measured at EMC. Dewpoint depressions near the squall line are 1 to 2 K less than the far environment, sug-
gesting moisture convergence has occurred. Surface data show the axis of maximum mixing ratio is across central Oklahoma. Near the surface, both soundings indicate nearly dry adiabatic conditions; however, the aircraft sounding is \( \sim 0.5 \) K cooler. The wind fields of the far and near environments are different also. Below 900 mb, both soundings indicate southeasterly flow (ground-relative), but above 900 mb, the near-environmental winds measured by the aircraft have a strong easterly component and the far-environmental winds a southerly component. This strong easterly component may be an indication of a cyclonic mesoscale circulation aloft. Additional aircraft observations at constant altitude in nearby locations are needed to determine how these winds fit into overall preline structure.

Line-relative flow in a vertical cross section perpendicular to the line and south of cell A \((y = 5 \text{ km})\) is shown in Fig. 16 (locations of vertical cross sections are shown in Fig. 6a). Ahead of the line, two pulses of upward motion (at \(x = -28\) and \(x = -17\)) are associated with the preline convective elements. Cell E has maximum reflectivity values aloft, indicating it is newer than cell E'. A third preline cell, at \(x = -20\), was not evident at the surface and has no label. Research aircraft data were collected along east–west flight legs south of these preline cells (see section 3d for details). A vertical cross section based upon this data extends the low-level flow field determined by the Doppler analysis into the nonprecipitating area east of the line. Southeasterly flow into the squall line is at least 3 km deep (maximum flight altitude) as far as 30 km ahead of the leading edge of the squall line. Both the aircraft data and the Doppler analysis (Fig. 17) show strong convergence at the gust front. However, the aircraft position of the
A gust front is above and east of the Doppler analysis position due to a difference in observation time of several minutes.

Within the mature convective region (Fig. 16), two areas of updraft exist in the upper levels, supporting the idea that older cells move to the rear of the squall system. Within cell A, the newer updraft tilts toward the west with height in the low- to midlevels. Weak descent is seen at or below the 7 km level west of the updrafts. Other cross sections show the main downdraft more clearly. The equivalent potential temperature ($\theta_e$) analysis determined from the aircraft sounding (Fig. 18) indicates that low $\theta_e$ air is present within the outflow air, implying that air from the higher levels is being brought towards the surface by convective downdrafts. Within the outflow, the lowest $\theta_e$ point value measured by the aircraft is 329 K, while the highest point value is 335 K; the mean is 331 K. Ahead of the gust front, 329 K air is found at ~3 km, and 335 K air is between 1.5 and 2 km, implying that convective downdrafts are transporting air (neglecting mixing) to the surface from as high as 3 km. The only possibility for the ultimate source of downdraft air is from ahead of the squall line, since Doppler, aircraft, and rawinsonde winds all indicate front to rear flow ahead of and within the line except for a small region behind the gust front. Ascertaining sources of downdraft air with greater accuracy requires a trajectory analysis from higher time-resolution data than are available for this case.

Flow within the stratiform rain region (Fig. 16) is from front to back of the system and contains weak (<5 m s$^{-1}$) updrafts and downdrafts. As shown in Fig.
A4, the error variance in vertical velocity increases to the west and has nearly the same magnitude as the vertical winds in this area. Therefore, progressively less confidence is placed in the calculated vertical motion field as one progresses westward within the stratiform region. In general, there appears to be significant horizontal variation in the vertical motion in the region, suggesting that forcing on small scales is operative. In calculating vertical motion based upon downward integration of the continuity equation, a nonzero constant upper boundary condition (2 m s⁻¹) has been assumed. This assumption seems realistic in the convective region where upward motion likely extends above the altitude where velocities are sampled, but seems unrealistic in the stratiform region. Computation of average vertical motion along a north–south line in this region (10–20 km west of the mature convection) shows ascending motion at all levels, increasing with altitude to ∼2 m s⁻¹ above 5 km to echo top. An experiment has been run assuming a 0 m s⁻¹ constant upper boundary condition for vertical motion (the outcome of which is not shown), resulting in apparently more realistic values of vertical motion. Computation of average vertical motion along a north–south line shows the region 10–20 km west of the mature convection contains weak downdrafts (∼0.5 m s⁻¹) below 5 km and weak updrafts (∼0.5 m s⁻¹) above 5 km, more consistent with other findings (Srivastava et al., 1986).

The 1434 EMC sounding (Fig. 3) shows the freezing level is ∼4 km AGL. Results from tropical squall line studies suggest the freezing level separates mesoscale ascent in the upper levels of the stratiform precipitation region from mesoscale descent below. None of the cross sections from the Doppler analysis of the Oklahoma squall line show a bright band as well defined as in the tropical squall line studied by Houze (1977). The bright band is not pronounced in this squall line; it can be seen only through careful examination of uninterpolated data from the CP-4 radar. A reflectivity enhancement of ∼5 dB is indicated by CP-4 observations at ∼3 km within region F; other radars are too distant to resolve the bright band.

The cross section through cell B at y = 45 km (Fig. 19) shows the reflectivity field has two maxima with associated updraft maxima. Cell B is similar in structure to cell A, but has a weaker updraft, a weaker downdraft and lower peak reflectivity values. The absence of pre-line convective elements (lack of mesoscale organization) associated with cell B may result in its comparatively weaker intensity. From 4–8 km, weak rear to front flow is present at the western edge of the stratiform region and may be evidence of rear inflow into the squall line.

To examine flow between cells A and B, a cross section is constructed along y = 28 km (Fig. 20). Similar to the mature convective cells, the low-level flow (<4 km) is from front to back while upper-level flow (>7 km) is westerly on the forward side of the line and easterly on the rearward side. Weak westerly flow can be seen in the midlevels (4–6 km) west of the stratiform precipitation area. Region F (a maximum in the low-level reflectivity field) exists west of the mature convection in all cross sections, but is not always well defined. Updrafts are weak and not well organized compared to those in major cells.

A north–south cross section at x = −53 km passes through cells A, B and C east of the highest reflectivity in each cell (Fig. 21). Strong vertical shear on the northern side of cell A results from strong, storm-top divergence. The updrafts in A, B and C coincide with increased reflectivity values with maximum reflectivity at or below 6 km. Between the major cells, downdrafts predominate over a few weak updrafts in the south to north flow throughout the squall line's depth.

![Fig. 13. As in Fig. 8 except at 1502 CST.](image-url)
c. Summary

To summarize the mean structure of the squall line, averages of the reflectivity and line-relative, horizontal winds are computed along the y-axis (a distance of 60 km) using the 1434 Doppler analysis (Fig. 22). Flow perpendicular to the squall line (Fig. 22b) shows inflow into the mature convective region is 6 km deep, with maximum flow occurring ≤2 km AGL, in agreement with the rawinsonde analysis (Fig. 5). As the mature convective region is entered, the flow maximizes at −15 m s⁻¹ at 3 km, then begins to decrease in intensity. Upper-level (12 km) divergence occurs here with flow reversing to westerly above 6 km in the forward anvil region of the squall line. In the stratiform region, a small reflectivity maximum at x = −95 and 2 km AGL is the averaged position of the bright band. Easterly flow generally weakens with height to 6 or 7 km where there is a minimum, then strengthens slightly above that. There is, moreover, weak (∼3 m s⁻¹), midlevel (3–8 km AGL) rear inflow into the stratiform region near the postline rainband. The postline rainband is relatively shallow (height ∼7 km) and contains easterly flow below 3 km and westerly flow above.

Flow parallel to the squall line (Fig. 22c) is, in general, stronger than the perpendicular flow. Below 2 km AGL and from the mature convective region to the postline rainband, winds within the cooled outflow have a northerly component. Elsewhere, the southerly component prevails. In the preline and mature convective regions, the flow increases with height to a maximum at 6 and 11 km AGL, respectively, then begins decreasing. In the stratiform precipitation region, the flow continues to increase to a maximum of
27 m s\(^{-1}\) at 11 km AGL. This area of strong flow occurs at the western edge of this region, above and east of the weak rear inflow.

As previously discussed, the averaged vertical motion field (not shown) indicates the stratiform region contains weak downdrafts (~0.5 m s\(^{-1}\)) below 5 km and weak updrafts (~0.5 m s\(^{-1}\)) above 5 km when a 0 m s\(^{-1}\) constant upper boundary condition is used during downward integration. These results appear consistent with findings from another midlatitude squall line (Srivastava et al., 1986) and a tropical squall line study (Zipser, 1969).

The horizontal flow of this squall line differs from another Oklahoma case documented by Smull and Houze (1985). Their case, 22 May 1976, shows midlevel rear inflow (~10 m s\(^{-1}\)) into the stratiform region with flow perpendicular to the squall line stronger than the parallel flow. In the 19 May 1977 case, the rear inflow is weaker and the parallel flow is generally stronger than the perpendicular flow. Low-level, southerly flow (Fig. 3) is much deeper on this day (~450 mb) than the 1976 case (~800 mb) and the westerly winds aloft are about twice as strong. The difference between the flow fields of the two squall lines may be a consequence of the differing environmental vertical shear profiles. More differences between these cases are presented in section 9.

8. Conceptual model of the 19 May 1977 squall line

A conceptual model (Fig. 23) of the 19 May 1977 squall line is developed from all observations and is valid for regions near mature convection. The squall line consists of four regions: preline convection, mature convection, stratiform precipitation, and a post-line rainband.

The preline convective region consists of new cells that gradually merge with the mature cells in the squall line due to differential motion of the cells and the line. This region is the source of air entering convective updrafts and downdrafts of the mature convection. Southeasterly inflow is 6 km deep into the line and has a low-level (~2 km) maximum of 15 m s\(^{-1}\).

The mature convective region consists of cells with vigorous updrafts and downdrafts. Updrafts tilt toward the west in the low and midlevels against the environmental shear vector, which is very weak in the low levels and strong at midlevels. As low-level air enters the leading updraft, some air becomes negatively buoyant due to water loading and descends, creating the low-level downdraft. Evaporative cooling of dry, midlevel air that has worked its way around major updraft regions may also support low-level downdraft production. Aircraft data suggest air may be descending in the downdrafts from at least as high as 3 km. At the surface, the downdraft causes cooling of ~5 K, contributing to a pressure increase of ~1 mb behind the gust front. Both aircraft and Doppler analyses show strong convergence at the gust front. At the tropopause, an area of mass divergence occurs and flow is westerly in the forward anvil region. As Newton (1950) suggested, this divergence over convergence couplet allows the low-level updrafts to be continuously reinforced, apparently contributing to the maintenance of this system for many hours. Severe events (hail, strong winds, and tornadoes) occur from cells in this region. Older cells move to the rear of this region and into the stratiform region.

The stratiform precipitation region is west of the mature convective region and is characterized by a low-level area of enhanced reflectivity with a relatively weak radar bright band. The reason for the weakness of the bright band is unclear. The rawinsonde analysis suggests mesoscale ascent is occurring in the stratiform region with a maximum of 70 cm s\(^{-1}\) from 5–7 km AGL, much as Leary and Houze (1979) proposed. Precipitation production may be occurring in this region of ascent. A suggestion of the mesoscale descent proposed by Zipser (1977) is seen but over a much smaller area due to sampling deficiencies. Doppler analyses show the flow perpendicular to the line in this region is easterly and weakens with height to midlevels, then increases slightly. Weak (<3 m s\(^{-1}\)) rear inflow is present from 3–8 km AGL at the western edge of the stratiform precipitation. Parallel to the line, the flow is southerly above 1 km, increasing to a maximum of 27 m s\(^{-1}\) at 10–12 km. Vertical motions derived by Doppler analysis suggest weak downdrafts occur below 5 km and weak updrafts occur above 5 km.

At the western edge of the system is a post-line rain-
Fig. 16. East–west vertical cross section through the 19 May 1977 Doppler-derived fields at the 1434 CST analysis time and along \( y = 5 \) km. See Fig. 6a for the location. Fields shown are (a) line-relative winds (m s\(^{-1}\)) along the cross section with solid lines representing updrafts \( > 5 \) m s\(^{-1}\) contoured every 10 m s\(^{-1}\) and dashed lines representing downdrafts \( > 2 \) m s\(^{-1}\) contoured every 5 m s\(^{-1}\) and (b) reflectivity (dBZ\(_v\)). Reflectivity is contoured every 10 dBZ\(_v\). Distances on the axes are east of Norman (horizontal) and local vertical. Panels are stretched in the vertical to illustrate line structure better.

Fig. 17. Averaged aircraft-measured winds and Doppler-derived winds and reflectivity along an east–west axis. Scale vector for the line-relative winds is at upper right. Doppler-derived vectors have solid arrowheads; aircraft-measured arrowheads are open. Reflectivity (dBZ\(_v\)) is shown with the heavy lines. The \( v \) component (m s\(^{-1}\)) is contoured where \( v > 0 \) m s\(^{-1}\) is from the south; solid lines are Doppler-derived, dashed lines are aircraft-measured. Negative \( v \) component is shaded.
This rainband is a relatively low-level phenomenon with maximum height of 7 km and is separated from the stratiform region by ~30 km. Doppler-derived flow perpendicular to the squall system in this region is easterly in the low levels (<3 km) and westerly in the midlevels (3–8 km). Parallel flow is northerly below 2 km and southerly above. Details of the distribution of Doppler-derived vertical motions are uncertain in this region. The reason for the formation of this rainband is uncertain.

9. Comparison of the 19 May 1977 squall line to other squall lines

Ogura and Liou (1980) documented the 22 May 1976 Oklahoma squall line. The line had a north–south orientation and propagated toward the east at 14.8 m s⁻¹. Its structure is similar to the 19 May 1977 squall line, with a precipitation zone about 100 to 140 km wide and the most intense convective elements limited to the eastern edge of the line. Comparison of a sounding from that day to the EMC sounding taken on 19 May 1977 shows the environment is warmer and drier at the surface on 22 May 1976. On 19 May 1977, moisture is present within a deeper layer with drying above the moist layer occurring more rapidly. Winds are stronger on 19 May 1977 at all levels and remain southerly through a deeper level.

Ogura and Liou (1980) analyzed rawinsonde data...
FIG. 20. As in Fig. 16 except with the cross section located along $y = 28$ km, between cells A and B.

FIG. 21. As in Fig. 16 except for a north–south cross section along $x = -53$ km. Distances on the axes are north of Norman (horizontal) and local vertical.
from 81 soundings taken on 22 May 1976. The most striking difference between the analyses of the two cases is the enhanced detail allowed when the number of soundings is increased an order of magnitude (8 vs 81). The eight soundings used for the 1977 analysis restrict the minimum resolvable scale to be about 115 km,
twice the average station separation. Significant features observed in the 22 May 1976 rawinsonde analysis and not in the 19 May 1977 analysis include: 1) the easterly wind component tilting against the environmental wind shear vector from the surface to the tropopause, implying a tendency toward conservation of easterly momentum in the vertical; 2) a strong convergence over divergence couplet within the stratiform precipitation area, which leads to significant sinking motion in the low levels; and 3) low-level upward motion within the convective region.

Comparison of the 19 May 1977 conceptual model (Fig. 23) to the 22 May 1976 conceptual model developed by Smull and Houze (1985) shows that basic similarities and a few important differences exist between the two cases. Both models have 1) a westward-tilted updraft along the leading edge of the line within the convective region, although the inclination angle of the updraft from the ground is about twice as large in the 1977 case; 2) a downdraft within the heavy precipitation core; 3) divergent flow from the updraft at the tropopause creating westerly flow in the forward anvil; and 4) easterly flow within the low-level, trailing precipitation area. The Smull and Houze model suggests descending motion in the low-level stratiform precipitation region, as well as easterly flow and ascending motion in the upper levels. Similar results are weakly indicated by the rawinsonde analysis for the 1977 case. The 1976 case shows a reflectivity notch near the surface on the western edge of the trailing precipitation area, created when westerly flow into the rear of the system converges with the easterly flow and produces a downdraft that erodes the echo. The rear inflow is observed in the 1977 case but is weaker (<3 m s⁻¹). Smull and Houze (1984, 1985) indicate the presence of a jet behind the main convective line near the location of the bright band. This jet is not observed on 19 May 1977 and the radar bright band is weaker. Additionally, the rainband along the western edge of the system is absent in the 1976 case.

Comparison of the 19 May 1977 conceptual model (Fig. 23) to the tropical squall line model from Ga-mache and Houze (1983) reveals similarities and differences. Preline convective elements are a feature common to both types of squall lines although details of their organization are undoubtedly different. They are incorporated into the main body of the line by differential motion of cells and line. Both systems have the mature convective region along the leading edge. Air within convective updrafts and downdrafts has its source region in the low levels ahead of the line. In the tropical case, the low-level updraft tilts against the environmental shear vector. In this study, the updraft tilts westward in the low and midlevels opposite to the sense of the environmental shear vector, which is very weak in low levels and strong in midlevels. Flow at all levels is from front to back in the tropical system with the exception of midlevel inflow into the rear of the trailing precipitation region. High-level divergence present in the midlatitude system is not usually seen in the tropical system, although Houze and Rappaport (1984) discuss one exception. In the stratiform region of the midlatitude squall line, flow is from front to back (except for a region of midlevel inflow at the back of the system) as in the tropical system. Significant flow is also occurring parallel to the squall line. In both the tropical and midlatitude systems, a suggestion of front to back ascending flow is in the upper regions of the stratiform cloud. The tropical system does not have the post-line rainband.

10. Summary and conclusions

This study has focused on the observed structure of the 19 May 1977 Oklahoma squall line. Tools used to study the structure of the squall line include a rawinsonde analysis, Doppler analysis at two times, a vertical cross section from aircraft data, and surface mesonet data. A conceptual model of this squall line is constructed. Comparisons are made to the 22 May 1976 squall line and to a conceptual model of tropical squall lines.

This squall line formed within a convectively unstable air mass near a preexisting convective system that had dissipated. Individual convective cells became oriented in a line and gradually merged to form a continuous squall line after ~6 hours. The line formed as the cells expanded and precipitation filled the areas between cells. The line was more than 300 km long and contained a north–south band of intense convective elements along its eastern edge. Mature cells in the line produced strong surface winds, heavy rains, hail, and several tornadoes. Squall line motion was from 270° at 10 m s⁻¹ while cells within the line moved from 202° at 10 m s⁻¹. Analysis reveals that the squall line consists of four areas: a preline convective region, a mature convection region, a stratiform precipitation region, and a post-line rainband.

The preline region contains small, growing cells that merge with the squall line due to differing motions of the cells and the line. The 6 km deep southeasterly inflow in this region is the source for air entering the vigorous updrafts and downdrafts in the mature convective region. Updrafts tilt towards the west in the low levels and towards the east aloft in the mature convection region; mass divergence exists near the tropopause with westerly flow in the forward anvil. Older cells appear to move toward the rear of the mature convective region into the stratiform region. The perpendicular component of flow in the stratiform region is predominantly easterly and decreases with height to midlevels; the parallel flow is for the most part southerly and maximizes at 11 km. Weak westerly flow occurs at the western edge of the stratiform region in midlevels. A weak bright band, produced by melting stratiform precipitation, is not a pronounced feature. A post-line
rainband is present at some north–south locations along the western edge of the system; it extends to a height of 7 km and appears to be convective in nature. Additional observations are needed to ascertain the reason that it is there; a possible cause is convergence of low-level, ambient flow into the rear of the system with cool outflow from the system.

Basic similarities exist between this squall line and that of 22 May 1976, although there are some important differences. The differences include a less prominent bright band, much weaker midlevel rear inflow, and the absence of an east to west jet near the bright band in the stratiform region in the 19 May case. This squall line perhaps shows more similarity to tropical squall lines than do other midlatitude systems that have been investigated. Features present in this system but not in tropical systems include more intense convection along the leading edge, a less-pronounced bright band, and reversal in the direction of relative flow in high levels ahead of the line. As in tropical squall lines, the flow near the ground is predominantly from front to rear in this case, whereas other midlatitude systems contain mainly rear to front flow.

Differences in small-scale structure between this squall line and others observed in midlatitudes likely result in part from the fact that this line was observed in a slightly earlier stage than lines studied by other investigators. Only two hours earlier, the squall line consisted of a broken line of thunderstorms, and several hours later it contained weaker convection and a more extensive area of stratiform precipitation. Another factor contributing to a differing structure was the environmental wind profile that, on this day, did not exhibit the strong low-level veering characteristics of many squall line situations. Stronger veering would have contributed to development of more pronounced midlevel rear inflow, the potential for additional rear to front flow near the ground, and very likely consequent changes in the overall mesoscale circulation. Clearly, more studies of this kind are needed with increased emphasis on understanding the evolution of such systems over a period of 4–8 hours or so. Knowledge of evolutionary characteristics would then allow for separating the influence of differing environments on system structure from structural characteristics related to evolution.

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APPENDIX

Radar Analysis

The dual-Doppler radar analysis is an extension of the variational formalism presented by Ray et al. (1980) and is designed to include data from more than two radars, resulting in an overdetermined system. Assuming that a radar located at \((x_i, y_i, z_i)\) observes a radial wind component \(V_i\) at a point in space defined by \((x, y, z)\) then the range to the observation is defined by

\[
R_i = [(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2]^{0.5}.
\]

Using standard least-squares methodology the \(u\) and \(v\) components are

\[
\begin{align*}
u &= \frac{\sum R_i V_i (x-x_i) S_{yy} - [\sum R_i V_i (y-y_i)] S_{xy} + [w + V_i] [S_{xy} S_{zz} - S_{yy} S_{xz}]}{S_{xx} S_{yy} - (S_{xy})^2} \\
v &= \frac{\sum R_i V_i (y-y_i) S_{xx} - [\sum R_i V_i (x-x_i)] S_{xy} + [w + V_i] [S_{xy} S_{zz} - S_{xx} S_{yz}]}{S_{xx} S_{yy} - (S_{xy})^2}
\end{align*}
\]

where

\[
\begin{align*}
S_{xx} &= \sum (x-x_i)^2 \\
S_{yy} &= \sum (y-y_i)^2 \\
S_{xy} &= \sum (x-x_i)(y-y_i) \\
S_{xz} &= \sum (x-x_i)(z-z_i) \\
S_{yz} &= \sum (y-y_i)(z-z_i)
\end{align*}
\]

\(V_i\) is the terminal fallspeed estimated from radar reflectivity (Joss and Waldvogel, 1970), and all summations are performed over the number of radars contributing data to the velocity estimates. Mass continuity is defined by

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} + \kappa w = 0
\]

where \(\kappa\) is the logarithmic change in density with height.
From downward integration of (A3), vertical velocity is computed by

$$w \left( k - \frac{1}{2} \right) = \left[ \frac{1}{\Delta z - \kappa / 2} \right] w \left( k + \frac{1}{2} \right) - \frac{\left( u_{i,j+1} - u_{i,j-1} \right)_{k}}{\left[ 2 \Delta x \left( 1/\Delta z + \kappa / 2 \right) \right]} - \frac{\left( v_{i+1,j} - v_{i-1,j} \right)_{k}}{\left[ 2 \Delta y \left( 1/\Delta z + \kappa / 2 \right) \right]} \quad (A4)$$

where $k$ is an index denoting vertical level, $i$ and $j$ are indices for horizontal grid points, and derivatives have been approximated by centered differences. Refined estimates of $u$, $v$, and $w$ are determined from (A2) and (A3) through iteration after the terminal fallspeed has been estimated from radar reflectivity. The three components are variationally adjusted using the vertically integrated mass flux form of the equation of continuity as a strong constraint. Adjustment is proportional to the variance of the velocity error.

The variance of the deduced wind component estimator can be expressed as

$$\text{var}[u_k] = \sigma_u^2 = \left\{ \sum \sigma_{u_i}^2 \left[ R_i (x - x_i) S_{yy} - R_i (y - y_i) S_{xy} \right]^2 \right\} \frac{1}{\left[ S_{xx} S_{yy} - (S_{xy})^2 \right]^2} \quad (A5a)$$

$$\text{var}[v_k] = \sigma_v^2 = \left\{ \sum \sigma_{v_i}^2 \left[ R_i (y - y_i) S_{xx} - R_i (x - x_i) S_{xy} \right]^2 \right\} \frac{1}{\left[ S_{xx} S_{yy} - (S_{xy})^2 \right]^2} \quad (A5b)$$

Covariance terms can be shown to be negligible for this analysis. The variance in the hydrometeor fallspeed estimate is denoted by $\sigma_u^2$ and the variance in the radial velocity estimate is $\sigma_v^2$. The variance in the vertical velocity estimate is expressed as

$$\text{var}[w_k] = \sigma_w^2 = \frac{1}{2} \left[ 1 + \left( \frac{1}{\Delta z - \kappa / 2} \right)^2 + \frac{1}{\left( \Delta z + \kappa / 2 \right)^2} \right] \sigma_u^2 \left( k + \frac{1}{2} \right)$$

$$+ \frac{\sigma_u^2}{\left[ 2 \Delta x \left( 1/\Delta z + \kappa / 2 \right) \right]^2} + \frac{\sigma_v^2}{\left[ 2 \Delta y \left( 1/\Delta z + \kappa / 2 \right) \right]^2} \quad (A6)$$

for downward integration, where $k$ is an index denoting height level. Derivatives have been approximated by centered differences and integration approximated through the trapezoidal rule.

Error variance fields (Fig. A1) are computed using (A5) and (A6) to assess the advantage, if any, of the overdetermined dual-Doppler analysis over directly solving for $u$, $v$, and $w$ given three nonconlinear components of wind (triple-Doppler analysis). Three radars are placed at the vertices of an equilateral triangle. Boundary conditions for the vertical velocity variance ($0 \text{ m}^2 \text{ s}^{-2}$, $16 \text{ m}^2 \text{ s}^{-2}$, and $100 \text{ m}^2 \text{ s}^{-2}$) are applied one-half grid interval above the top of the analysis domain and downward integration is performed. Solutions are shown at 1 and 10 km. At each grid point, the variances of the radial velocity estimate from each radar and the terminal fallspeed estimate are assumed to be $1 \text{ m}^2 \text{ s}^{-2}$. Grid spacing is 2 km in the horizontal and 1 km in the vertical.

All plots for the overdetermined dual-Doppler vertical velocity error variance fields (Fig. A1) exhibit a characteristic pattern. The absolute minimum of the variance is located at the center of the radar network. Minimum values extend outward from the network center and across the midpoint of each baseline. Variance increases behind each radar. These patterns reflect the error variance plots of a two-radar analysis scheme, where lobes of minimum variance are located on either side of the baseline connecting the two radars and error approaches infinity at the baseline. If the dual-Doppler error variance (Doviak et al., 1976) is calculated for each pair of radars, the patterns shown in the plots of the error variances for the overdetermined dual-Doppler equations are explained. The absolute minimum of error variance in the center of the triangle reflects the intersection of three minimum lobes from a typical dual-Doppler pairing of the three radars. The local
minimum of variance outward from the baseline between each radar pair is the other minimum lobe from the dual-Doppler analysis. Variances along the baseline between radars do not approach infinity due to the presence of the third radar. Error variances in the overdetermined equations increase behind each radar due to the intersection of two baselines at each site.

To verify the advantages of the overdetermined dual-Doppler radar analysis solved by the least-squares technique, the triple-Doppler error variance equations (Ray and Sangren, 1983) are solved using two methods and a comparison is made. First, the equations are solved directly for $\sigma_u^2$, $\sigma_v^2$ and $\sigma_w^2$. Second, the horizontal error variances are computed directly and the vertical velocity error variance computed by downward integration of the anelastic form of the equation of continuity similar to the overdetermined dual-Doppler method. Boundary conditions are $0 \text{ m}^{-2} \text{ s}^{-2}$, $16 \text{ m}^{-2} \text{ s}^{-2}$ and $100 \text{ m}^{-2} \text{ s}^{-2}$. Horizontal grid spacing is $2 \text{ km}$ and vertical grid spacing is $1 \text{ km}$.

Results from direct calculation of the vertical velocity error variance using the triple-Doppler equations (first method) show that at $1 \text{ km}$ (Fig. A2a) and $10 \text{ km}$ (Fig. A2b), error is a minimum directly over radars. At $1 \text{ km}$, the error variance increases rapidly at small distances away from any radar. The solution for error variance approaches infinity as the height of the analysis grid approaches the plane defined by the three radar heights ($z = 0 \text{ km}$ for this case). At $1 \text{ km}$, comparison of the direct solution of the triple-Doppler equations to the overdetermined dual-Doppler equations shows the dual-Doppler solution yields a greater area of small error for all boundary conditions. At $10 \text{ km}$, the overdetermined dual-Doppler equations produce a smaller minimum variance than the direct triple-Doppler solution only when a boundary condition of $0 \text{ m}^{-2} \text{ s}^{-2}$ is used. However, the area of decreased error is larger for the overdetermined case since the gradient of the error is smaller.

For the second method, the variance of the vertical velocity error (Fig. A3) of a triple-Doppler analysis is computed by integration of the continuity equation using the horizontal error variances. Smaller error variances are obtained with downward integration of the equation of continuity over direct solutions of the triple-Doppler equations only when a boundary condition of $0 \text{ m}^{-2} \text{ s}^{-2}$ is used. Like the overdetermined dual-Doppler method, the error variance computed with $16 \text{ m}^{-2} \text{ s}^{-2}$ boundary condition yields smaller error over a larger area than the direct solution.

Smallest errors are found at higher altitudes by solving the triple-Doppler equations directly, but the area of small error variances is greater in the overdetermined dual-Doppler method, giving better vertical velocity estimates over a larger area. Also, vertical velocities show continued improvement near the ground with the dual-Doppler method whereas the triple-Doppler, direct solution for the vertical velocity error variance deteriorates rapidly near the ground due to the $1/z^2$ dependence. When both triple- and overdetermined dual-Doppler equations are integrated downward, the same conclusion is reached for both the $1$ and $10 \text{ km}$ levels. The above findings are also true for upward integration of the overdetermined dual-Doppler equations as shown by Kessinger et al. (1983).

To summarize, the overdetermined dual-Doppler analysis technique gives improved results over the triple-Doppler analysis technique when integration of the continuity equation is used to obtain the vertical velocity error for both techniques. In most cases, use of the overdetermined equations results in an increase in areal coverage of the region characterized by reduced velocity error variance. Errors computed for the overdetermined case are a function of the grid spacing, which is not true of the direct solution for the triple-Doppler case. Finally, because the number of radars with data at a grid point varies over any analysis domain, the overdetermined dual-Doppler method offers greater flexibility.

To better interpret results from the overdetermined analysis for the 19 May 1977 case study, the error variance for vertical velocity is determined from (A5) and (A6) using the locations of the NOR, CIM, CHILL and

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**Fig. A2.** Variance of error in the vertical velocity ($\text{m}^{-2} \text{ s}^{-2}$) at (a) $1 \text{ km}$ and (b) $10 \text{ km}$ as computed directly with the triple-Doppler equations using three arbitrary radars located at the cross hairs.
CP-4 Doppler radars within the 1434 analysis domain. Because each grid point has 2–4 radars contributing data, significant differences can occur in the actual error variance over fairly small distances. At 5 km (Fig. A4a), errors are smallest near the center of the radar network and are large in areas where data from only two radars exist (−30, 2) or data from a key radar do not exist [i.e., CHILL at (−68, 28) and (−100, 44)]. Errors are larger within the convective line along x = −140 km because the location is remote from the network center and only two radars are scanning this area. This figure illustrates that the Doppler radar analysis results must be interpreted with care. Unrealistic or noisy vertical velocity patterns are expected as distance from the center of the radar network increases (i.e., within the western portion of the stratiform precipitation region and the post-line rainband). The horizontal error analysis has characteristics similar to the vertical (with reduced magnitude) and affects the vertical velocity errors due to the integration procedure. At the 1502 analysis time (not shown), errors in the vertical velocity are larger because NOR did not collect data.

For comparison, the error variance of the vertical

![Graph showing variance](image)

**Fig. A4.** Error variance for vertical velocity (m s⁻¹) at 5 km, computed using the overdetermined dual-Doppler error variance equations and the locations of the NOR, CIM, CHILL and CP4 radars. See Fig. 1 for CHILL’s location relative to the analysis grid. Downward integration is used within the domain of the 1434 CST Doppler analysis. (a) Variance is computed when radial velocities are available from a radar. Each radar does not necessarily contribute data at each grid point. (b) Variance is computed assuming radial velocity data exists from all radars at all grid points.

**Fig. A3.** Variance of error in the vertical velocity (m² s⁻²) at 1 km (a–c) and 10 km (d–f) as computed by downward integration of the continuity equation and the triple-Doppler equations using three arbitrary radars, located at the cross hairs. Boundary conditions for vertical velocity error variance are as in Fig. A1.

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