The Flanking Line, a Severe Thunderstorm Intensification Source

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ABSTRACT

An organized persistent severe thunderstorm on 25 June 1969 blends elements of the classic supercell (Browning and Donaldson, 1963) and the multicell storm (Marwitz, 1972), as revealed by detailed surface and radar data. Changes in supercell strength reflect contributions of cells from a flanking line that overtake and combine with the main storm. One cell contributed to an intensified mesocore depression and increased surface convergence as the cell merged with the supercell weak echo (updraft) region. Cells move both to the right and left as well as with the mean winds. Surface data reveal distinctly arranged surface discontinuities, a large persistent mesocore depression, an associated convergence area, and one principal downdraft.

1. Introduction

The Thunderstorm Project (Byers and Braham, 1949) shows air-mass thunderstorms as groups of convective cells (updraft-downdraft couplets), each a few kilometers in diameter. Browning and Ludlam (1962) and Browning and Donaldson (1963) developed the concept of a large quasi-steady supercell, typically 20 to 50 km in diameter. The squall line, another basic storm type, is a lateral alignment of persistent cells (Newton, 1963; and others). Marwitz (1972) proposed a classification system including storms in an environment of strong vertical wind shear where one large cell changes through periodic discrete propagation on the front flank.

This study examines an Oklahoma thunderstorm (25 June 1969) which blends multicell and supercell types while propagating both discretely and continuously. Radar and surface data show that one of several cells developing within a flanking line led to intensification of the adjoining supercell through a merger process. Merger effects are studied in the context of both overall storm structure and behavior.

2. Instrumentation and data handling

The National Severe Storms Laboratory (NSSL) mesonetwork (Fig. 1) during 1969 recorded surface wind speed and direction, barometric pressure, relative humidity, temperature and rainfall at stations spaced about 11 km apart. Sanders (1965) gives complete instrumentation, calibration, recording, and data sorting techniques used in the network operations.

Surface data from 1530 to 1840 (all times CST) on 25 June were reduced and systematic errors removed using each station’s calibration records. Five-minute averaging and smoothing reduced uncertainties of ±22.5° in instantaneous wind direction. Station pressure biases were eliminated by referencing pressure deviations to individual 3 h linear trends defined by regression analysis.

The objective analysis uses asynoptic data as described by Barnes (1973). Wind speed and direction, divergence, vorticity, temperature, relative humidity, wet-bulb potential temperature and pressure were analyzed to obtain data at 3.175 km grid intervals (Fig. 1). Significant surface features were matched with recorded radar echoes.

The NSSL WSR-57 10 cm radar with a 2° conical beam width scanned in azimuth at a rate of 1.5 rpm. The WSR-57 return signal was processed, recorded on magnetic tape, and displayed remotely (Wilk and Kessler, 1968; Sirmans et al., 1970). Range-height data also were recorded from a 4.7 cm MPS-4 radar with a 1.4° conical beam width. During each scan, 35 mm cameras automatically photographed both radar displays. The WSR-57 antenna continuously cycled in elevation from 1° to 4° (at 1° intervals) as the storm moved across the network. Digital data were converted to a constant-altitude cross-section presentation at 1 km intervals from 1 to 4 km AGL (ground level reference is 381 m MSL). Cross-section contoured displays were transferred to network base maps.

3. Storm history

Jessup (1972) reported the details of the synoptic situation. In general, thunderstorms were prefrontal with a low-level, warm, very moist layer (wet-bulb potential temperature ~ 26°C, dewpoint ~ 22°C). The Lifted Index was −6 and the average vector shear in the cloud-bearing layer (850 to 100 mb) was 6.5 × 10^-4 s^-1, as revealed by 0600 and 1800 soundings from
Tinker Air Force Base located 18 km northeast of the radar site. The 0600 hodograph (Fig. 2) indicates strong low-level veering, a low-level jet, and upper tropospheric flow of about 30 m s\(^{-1}\).

Storm behavior and path from inception at 1455 until around 1600 when it moved into the network are briefly discussed by Jessup (1972). It moved with the mean flow in the cloud bearing layer initially, from 227° at about 24 m s\(^{-1}\). As the storm passed into the network, it slowed and turned to the right. The storm complex as a whole moved from 248° at 9 m s\(^{-1}\) through the network while the weak echo region (WER) moved from about 248° at 13 m s\(^{-1}\).

The first hail reported by cooperative observers occurred at 1545 and the last occurred at about 1945. Reports of 3–4 cm diameter hail were common, with the average size 1.5 cm and largest 5 cm. Reports of National Weather Service, Air Force, cooperative observers, U. S. Department of Commerce (1969), and radar data indicate that the storm produced hail (as data resolution permits) continuously.

The author first clearly viewed cloud base beneath the WER around 1640. Organized cyclonic circulation was observed, with cloud base estimated at 1 km AGL. Around 1705 a funnel cloud formed above the thunderstorm cold air outflow; the funnel's lowest visible portion extended below 500 m AGL. At 1707, station 5D recorded a sharp pressure dip of 3.8 hPa and wind gusts of 35 m s\(^{-1}\) as the funnel passed near the station. The storm later produced a damaging tornado about 40 km northeast of the radar.

4. Radar echo characteristics

Pertinent radar echo features from 1616 through 1700 are shown for the 1 km AGL level at 5 min intervals by contoured cross-section displays (Fig. 3). In the echo series, a prominent feature (especially at 1630, center located 11 km north of 5B) is the apparent anticyclonic lee eddy which emerges from the echo and moves away. Structure and physical implications are considered by Lemon (1976).

At 1616 two adjoining echo reflectivity masses exceeded 46 dBZ. The first core 8 km west of station 6B is the center of the storm under study. The second reflectivity mass or storm was centered 15 km west of the first.

a. Supercell structure

The easternmost storm maintained the supercell structure (Browning and Donaldson, 1963; Browning, 1964) as indicated by Lemon (1974). Above the storm vault or WER one maximum echo top was maintained at 18.5 km AGL through the analysis period as indicated by the National Weather Service WSR-57 radar at Oklahoma City. A distinctive supercell feature is the hook appendage which developed at 1630, 3 km west of station 7A (Fig. 3). The hook moved with the WER and was tracked into the radar ground clutter.

b. Storm motion

Marwitz (1972) established that at least one primary source for rightward supercell motion is continuous propagation. While new updraft forms on the right of the WER, old updraft dissipates on the left. The 25 June storm moved through the network 21° to the right of the mean winds. Discrete propagation occurred between 1616 and 1644 as developing cells in a line on the right rear flank merged with the storm. (This process is detailed in the next section.) From 1644 through 1700 the storm continued moving to the right although discrete propagation was not
observed. Continuous propagation, as Marwitz (1972) described, might explain the rightward motion without discrete propagation evidence. A complicating factor of thunderstorm updraft rotation existed in this case. Fujita (1965) and Charba and Sasaki (1971) have proposed the Magnus effect to explain storms deviating
to the right of the mean winds. This Magnus effect may have contributed to deviate storm motion.

c. Multi-cell structure

Unlike supercell storms synthesized to date, this storm propagated *discretely* during part of its supercell stage. At 1616 (Fig. 3) an echo band extends southward about 13 km south-southwest of the storm’s core. The echo line’s cellular nature is found at higher levels (not shown). The line lies parallel to and behind the advancing gust front and probably was initiated by convergence and associated vertical motion at the discontinuity. The echo band, a cumulus congestus "flanking line," projects more directly westward between 1635 and 1644. Henderson (1968) states that this cloud-line structure representing major storm inflow is quite common in single-cell storms. Dennis *et al.* (1970) described the flanking line as “feeder clouds.” The author, who observed this area visually during the early stages of Fig. 3, noticed a line of rapidly growing “stair-stepped” cumulus merging with the main cumulonimbus from the southwest.

Echo segments identified as cells are so named because 1) the echo segment is resolvable with height as a reflectivity core (or tower on the RHI radar); and/or 2) the echo segment’s general structure and movement were quasi-steady with time. First echo height and precise times of new cell development are unknown due to the small maximum WSR-57 antenna...
structure. The first was produced by a moderate thunderstorm moving through the network about an hour earlier, the “wind shift line” or WSL (Fig. 3, 1616). The leading outflow edge (“first gust” or “gust front”) advanced over nearly all the northern and western network before 1600. Continued slow eastward motion is marked by a wind shift from southerly to southwest or west, with minor speed changes, unchanged or slight pressure rises, and $\theta_w$ falls of 1–2°C (Fig. 5). By 1635 the discontinuity is quasi-stationary, near the eastern and southern network extremities. Near the surface convergence area, the WSL returns north and northeastward (warm front symbols, Fig. 3, 1616).

The “surge line” (SL), part of one “thunderstorm scale” air-mass interface, is embedded within a light precipitation region, and its passage is followed by an increase in wind speed and gustiness. Commonly, wind direction shifts only slightly as the SL passes. High relative humidity (90–100%) and a pressure trough further characterize the surge line. Within a few minutes after the surge line passage, $\theta_w$ drops sharply (3–5°C) as shown in Fig. 5.

The second part of the joint discontinuity, labeled MCO or “mesoscale cold occlusion,” has a similarity in its location to the synoptic-scale cold occlusion. The MCO differs markedly from the SL because the wind direction shifts abruptly from northeast to southwest as wind speed increases with MCO passage. The area a few kilometers ahead of the MCO is the location of the storm mesodepression and surface roots of the supercell updraft (Sections 5a and 5b and Fig. 5). Inflow to this region originates from a moist rainy downdraft of primarily recirculated surface air (divergence shown ahead of the SL, 1615–1625) with $\theta_w$ values of 25–26°C. Behind the MCO air with $\theta_w \approx 21°C$ has descended from mid-levels (decreased from 0600 to 1800 soundings).

The last discontinuity or “gust front” (labeled GF) resembles the Charba (1974) gust front. Pressure starts to rise a few minutes before gust front passage, and the wind shift, gustiness and temperature break occur together as it passes. Winds shift from south-southeast to northwest, then gradually to the northeast. A warm, very moist air mass with $\theta_w$ values of 27°C is found along and south of the GF at the flanking line updraft roots.

At the juncture between MCO and SL (small darkened triangle, Fig. 3) a closed cyclonic circulation or mesocyclone exists. Individual station wind records clearly show system development around 1640.

5. Surface weather

A distinctive arrangement of meteorological discontinuities is associated with the storm’s surface

![Diagram of wind velocity and direction](image)

**Fig. 4.** Mean wind (MW) velocity and direction, and cell paths relative to surface network.
to other surface features in Fig. 5 and can be compared to Fig. 3 for locations relative to the radar echo. Fig. 6 includes the objectively determined maximum pressure deficit of the major mesodepression (L₁, Fig. 5) as a function of time. Barnes (1974) presented evidence showing separation of circulation center and mesodepression. This study shows that, at the time of greatest pressure deficit, lowest pressure coincides with the circulation center; at other times circulation apparently is too weak to bring about coincidence. Although the lowest pressure deficit (Fig. 6a) based on objective analysis with smoothing is $-2.5 \text{ hPa}$, the unsmoothed processed data indicate a low of at least $-3.1 \text{ hPa}$.

The effect of new cell merger with the supercell possibly explains the pressure center location shifting from the east to coincide with the mesocyclone center (Fig. 5). At 1625, a second low (L₂) appears southwest of the major supercell mesodepression (L₁). Low L₂ in cool surface air behind the gust front likely reflects the updraft belonging to cell C1. L₂ moves northeast and is beneath the newly developed hook echo while a narrow pressure trough extends further northeast and joins with the major mesodepression. At this time C1 can no longer be distinguished on radar. By 1640, L₂ is completely absorbed by L₁. From 1630 to 1635 the lowest pressure location (relative to the ground) in L₁ remains unchanged while its location relative to the wave crest shifts from east to near the crest or mesocyclone.

Two other events coincide with the merger process between 1625 and 1640. In the area where cell C1 has merged with the supercell, the hook echo forms and is maintained. Second, pressure within the major mesodepression lowers steadily and most rapidly during its merger with L₂ (Fig. 6a). Pressure lowering within L₁ directly affects associated convergence (Section 5b, Fig. 6).

The primary mesohigh develops or is first detected at 1630 beneath C3 at the west edge of the network. This region, associated with the precipitation core and downdraft, builds steadily and becomes the principal thunderstorm high. Central pressure excess values of 2.0 hPa are reached. Other less significant pressure centers also occur.

b. Divergence

The important convergence region (for storm strength and organization) centers near the MCO, although some convergence also characterizes other discontinuities. The convergence area ($-1.5 \times 10^{-3} \text{ s}^{-1}$, Fig. 5) lies along and east of the MCO becoming more symmetric about the line with time. The region moving with the storm WER reaches maximum strength with greatest spatial coverage when surface pressure in mesodepression L₁ is lowest (Fig. 6). The strengthening and increased convergence coincide with later merger stages of depressions L₂ and L₁ and the corresponding deepening of L₁. Increased surface wind gusts peaking at 35 m s⁻¹ are also associated with the deepening of the supercell mesodepression and increasing convergence.

The principal divergence region enters the network’s west edge and throughout the analysis associates with the principal downdraft near the storm’s rear edge. Air associated with this divergence originated in mid-levels.

6. Cell merger with supercell

Streamlines coupled with $\theta_e$ fields indicate that much of the surface mesocyclone inflow originated from a moist rainy downdraft. The potential temperature ($\theta$) of supercell inflow averaged 2.4 K less than in the air south of the GF in cell updraft source regions. Entrainment of cell updraft C1 into the severe thunderstorm WER probably contributed to increased buoyancy and vertical acceleration of the supercell updraft in three ways: (i) increased volume of undiluted updraft air, (ii) addition of higher $\theta$ air, and (iii) increased convergence in the mesocyclone responding to falling pressure (induced by the warmer more buoyant air aloft). Microphysical cloud changes, such as rapid freezing of large quantities of supercooled water within the flanking line cumulus tower as it merged with the glaciated supercell, may also have contributed to increased updraft energetics. Moreover, increased vorticity concentration associated with increased convergence may have enhanced updraft rotation, which would further increase low-level convergence and decrease mid-level entrainment, as shown by Ward (1967). The overall effect of the cell merger is increased updraft velocity (and possibly rotation as evidenced by hook echo formation) in the supercell, bringing decreased surface pressure and increased surface convergence.

7. Summary and conclusions

A severe thunderstorm’s radar and surface structure has been examined in detail. Radar indicated one large supercell with embedded smaller cells originating from a line of flanking towering cumulus on the right rear quadrant. Most small cells moved through the supercell echo, weakened, and dissipated on the left flank (as in documented multicell storms). However, one cell (C1) lost its identity in the strong reflectivity gradient on the WER rear edge. A hook echo then developed and persisted in that location.

The structure and organization of surface wind discontinuities (similar to synoptic-scale low-frontal organization) apparently led to a significant impact on the supercell updraft by cell C1. Supercell surface
updraft roots were ahead of the mesoscale cold occlusion and north of a warm front-like portion of the wind-shift line. Surface roots for the flanking line cells were located south of the gust front in warmer moist ambient air having a potential temperature 2.4 K greater than the supercell updraft roots.
As C1 merged with the thunderstorm WER, the supercell mesodepression deepened, convergence magnitude and aerial coverage increased, and surface wind gusts increased to severe proportions. Entrainment of the warmer cell updraft by the supercell apparently contributes to increased buoyancy and vertical acceleration and possibly rotation.

A proper storm classification system should include supercell storms with flanking lines. NSSL radar film plus visual observations (Golden, 1972) indicate that supercell storms with accompanying flanking lines are common, often severe, and relatively long-lived in Oklahoma. The longevity and severity of these storms is probably due in part to entrainment of flanking cells.

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**Fig. 6.** Time variations of objectively analyzed surface values of (a) minimum pressure of supercell associated mesodepression L1, (b) maximum convergence associated with L1, and (c) planimeter-determined areal coverage within $-1.5 \times 10^{-3}\text{ s}^{-1}$ convergence contour.