Formation of Mesoscale Lines of Precipitation: Severe Squall Lines in Oklahoma during the Spring

HOWARD B. BLUESTEIN*

School of Meteorology, University of Oklahoma, Norman, OK 73019

MICHAEL H. JAIN

Weather Alert Radar Network (WARN), Weldon, OK 74881

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ABSTRACT

Four distinct kinds of severe, mesoscale convective-line development are identified in Oklahoma during the spring based on the analysis of an 11-year period of reflectivity data from the National Severe Storms Laboratory's 10-cm radar in Norman, Oklahoma. The primary classes of line formation are broken line, back building, broken areal and embedded areal. Each is described in detail, along with illustrative examples. Comparisons are made with other observations and with numerical model simulations. The former two classes of line formation have been previously documented, while the latter two have not. Only the broken-areal squall line has been realistically simulated numerically.

The environment for each of the types of line development was determined from data from the standard National Weather Service surface and upper-air networks and from special rawinsonde launches. It was found that broken-line formation tends to occur along cold fronts in a multicell environment, while back building occurs along any boundary in a supercell environment. The former formation is associated with a steering level with respect to cell motion, while the others are not. A steering level with respect to line motion exists around 6 or 7 km MSL in all cases. Cells within back-building squall lines have high relative helicity, like supercells, while cells within broken-line squall lines have low relative helicity. Most lines were oriented approximately 40° to the left of the pressure-weighted vertical shear vector in the troposphere, along the pressure-weighted vertical shear vector in the lowest 1 km and at a large angle to the shear somewhere in the lower portion of the middle troposphere.

1. Introduction

While the original use of the term squall line as a linearly oriented region of gusty winds comes from French mariners (Durand-Greville, 1892; Talman, 1907), descriptions by others of the squall line as a phenomenon have also appeared in the literature (e.g., Ley, 1878). Before the development of frontal theory, cold fronts were included in the class of phenomena known as line squalls or squall lines (Lempfert and Corless, 1910; Bjerknes, 1919). The use of the expression squall line was later restricted to lines of convection not associated with fronts (Byers and Braham, 1949). The term instability line was soon officially accepted by the international meteorological community (Fulks, 1951), and the term squall line was reserved for mature instability lines (Huschke, 1959). Ironically, the "squall" aspect of the squall line had been deemphasized. It was, however, also recognized that the conceptual separation of squall lines from frontal bands was not necessarily prudent since it was observed that the two often appeared to be indistinguishable from each other (Brunn, 1953). Miller (1975), Lilly (1979), and Houze and Hobbs (1982) have also recently argued that frontal and nonfrontal lines of thunderstorms represent similar phenomena. In addition, they emphasized the electrical aspects of squall lines, since even rainbands sometimes exhibit a surface wind shift and temperature change just as squall lines do. Houze (1977) and Zipser (1977) further broadened the concept of the squall line to include the anvil and the stratiform precipitation and cool air often found behind the gust front as part of the squall line system. Carbone (1982) proposed that there is a spectrum of types of precipitation bands ranging in intensity from those with diffuse, weak vertical motion to those composed of severe, deep convection. We will therefore define the squall line loosely as a linearly oriented mesoscale convective system* (Maddox, 1980) whose less

* Present affiliation: On sabbatical leave at the National Center for Atmospheric Research, Boulder, CO 80307. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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1 We use the term "convective" in the broadest sense, i.e., relating to the transport of entropy and energy by fluid motion.
intense specimens may not even be driven by buoy- 
ancy, and which have wind shifts and cool air outflow like the more intense members of their species. Thus, 
strong squall lines may contain supercells as building 
blocks, while weaker squall lines may be composed 
mainly of ordinary cells (Browning, 1977) or even pre-
cipitation elements forced by instabilities not exclu-
dively due to gravity, such as conditional symmetric 
instability (Bennetts and Hoskins, 1979; Emanuel, 
1983).

Although there have been many detailed observa-
tional case studies about the structure of intense, ma-
ture squall lines in midlatitudes and the tropics (e.g., 
Newton, 1950; Sanders and Paine, 1975; Ogura and 
Chen, 1977; Sanders and Emanuel, 1977; Houze, 1977; 
Zipser, 1977; Ogura and Liou, 1980; Elmore, 1982; 
Kessinger, 1983), there has been no systematic inves-
tigation of the ways in which the “building blocks” 
that form the mature squall line system initially become 
organized into a line. The purposes of this study are 
to classify the types of radar-observed severe, squall-
line formation that occur in Oklahoma during the 
spring, and to relate each type of squall-line formation to a composite environmental sounding and to the 
synoptic pattern.

The four classes of line formation we found from 
our scrutiny of the radar data are discussed in Section 
2. Satellite observations are discussed in Section 3. In 
Section 4 we relate our analyses of surface and upper-
air data to each type of line formation. The results 
detailed in Sections 2, 3 and 4 are discussed in Section 
5 in the context of other observations, numerical model 
simulations and dynamical theories. In Section 6 our 
results are summarized, and in Section 7 some unsolved 
problems are discussed.

2. Classification based on the analysis of radar data

The 10-cm WSR-57 radar operated by the National 
Severe Storms Laboratory (NSSL) in Norman, Okla-
ahoma was our source of data. Photographs of the PPI 
display at various elevation angles for the eastern, cen-
tral and western areas of Oklahoma were available on 
35-mm film at time intervals as short as 30 sec. Mi-
crofilm covering an 11-year period from 1971 through 
1981 were viewed for NSSL’s prime data-collection 
months of April, May and June. During six years of 
the 11-year period, radar photography was terminated 
in mid-June. We found that our inspection of the se-
quences of photographs was made easier and more ef-
fective by using a time-lapse projector. It is very im-
portant to use a sequence of photographs taken at fre-
quently intervals, since the formation of lines of radar 
echoes often occurs on time scales as short as ten min-
utes.

Lines of radar echoes at 0° elevation angle were 
identified according to the specific set of criteria used 
by several federal agencies in the United States (U.S. 
Departments of Commerce and Defense, 1980). A line 
is defined as related or similar echoes that form a pat-
tern exhibiting a length-to-width ratio of at least five-
to-one. They are at least 50 km long, less than 50 km 
in width and they persist for at least 15 min. We con-
sider features of these space and time scales to be me-
oscale. Thus, thin lines (less than 10 km in width) of 
ordinary cells which go through their life cycles (on a 
time scale of 10–20 min) without the subsequent for-
mation of new cells are not considered.

During the 11-year period approximately 150 cases of 
mesoscale lines of radar echoes were observed. On 
several days there were more than one case (e.g., early 
in the morning and later at night). Each case was treated 
separately. We decided to restrict ourselves, in this 
study, to only lines that were associated with severe 
weather events. Specifically, severe weather events in-
clude tornadoes, funnel clouds, surface wind speeds 
greater than 25 m s⁻¹ and hail larger than 1.9 cm in 
diameter. Broadly speaking, severe convective lines are 
those that are damaging or potentially damaging (e.g., 
if the wind speed is high, but there are no structures 
to damage). It must be recognized that these criteria 
are arbitrary, and that our main purpose in neglecting 
nonsevere lines is to focus only on the most intense 
squall lines. We acknowledge that we may be missing 
some systems which cause damage due to flooding. In 
addition, it is unlikely that convective lines in which 
wind speeds are slightly under 25 m s⁻¹ or that hail is 
just under 1.9 cm in diameter are different dynamically 
from the severe systems. Storm Data and information 
from the University of Oklahoma and NSSL storm 
intercept teams were used as sources for severe weather 
reports. Of the 150 cases of convective lines we iden-
tified, 86 (57%) were associated with severe weather 
events. Severe squall lines were most common in May, 
when on the average 3.5 occurred; 2.6 and 2.4 oc-
curred on the average during April and June. (The June 
average was adjusted to reflect the days when the radar 
was shut down in mid-June.) Some of these severe cases 
were not included in our working sample because line 
formation occurred outside the range of the radar, the 
lines formed before the radar or camera were turned 
on or the quality of the radar photographs was poor. 
The working sample therefore consisted of 52 cases. 
Although there were some changes in the quality and 
the intensity contours of the PPI display over the years, 
it is felt that our working sample captures the essence 
of the formation process without bias toward any time 
period or any type of formation. This is supported by 
the relatively uniform distribution of yearly squall-line 
cases shown in Table 1.

Twelve of the 52 squall-line cases in the working 
sample were either too complicated to categorize with 
any confidence or formed a class of line formation in 
which there was only one other member. The final
working sample of squall lines consisted of 40 cases—only slightly more than one quarter of the total number of original line cases.

Most severe squall-line development occurred in one of the four ways depicted in Fig. 1. Broken-line formation is the appearance of a line of discrete cells, each cell forming at nearly the same time, and the transformation of the line of cells into a solid line as the area of each existing cell expands and new cells develop in between the older cells. This type of squall-line formation has been documented to some extent by Newton (1963), Fankhauser (1974); see his Fig. 4) and Koch and McCarthy (1982). An example of broken-line formation is shown in Fig. 2.

Back building consists of the periodic appearance of a new cell upstream, relative to cell motion, from an old cell, and the resulting merger of the new cell with the old cell as the former expands in area and moves into the latter. Although this process is usually initiated from a single cell, it can also occur to a group of widely spaced (much longer than the cell length) cells, each of which can back build to form a line or line segment. The back-building mode of line formation has been observed in many early investigations of squall line behavior. Brooks (1946) described "... new cells on one side and dissipating cells on the opposite side." Abdullah (1954), on the basis of an isochrone analysis by Brunk (1949), remarked that "... it (i.e., the squall line) seems to start in a very limited region, usually at the left side of the basic flow in the warm sector. It then grows by extending in the meridional direction, usually toward the right side of the flow." Stout and Hiser (1955), Newton and Katz (1958), Newton (1963) and Newton and Fankhauser (1964) noted similar behavior. In a study of storm formation in Colorado, Henz (1973) referred to the result of back-building when there is a localized region of new cell formation as a "hot spot line." Figure 3 shows an example of a back-building squall line.

The development of an amorphous area of relatively moderate-to-intense cells into a solid line of convection is called broken-areal formation. An example of broken-areal formation is given in Fig. 4.

The type of squall-line development which occurred least frequently is known as embedded-areal formation. This occurs when a convective line appears within a larger area of weaker, stratiform precipitation. This phenomenon is illustrated in Fig. 5.

The broken-line, broken-areal and embedded-areal formation processes take place on a time scale of 30–90 min and are not repeated. The back-building process

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**TABLE 1.** List of cases. (Dates shown are for the local time of squall-line formation.)

<table>
<thead>
<tr>
<th>Type</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Broken-line squall lines</strong></td>
<td></td>
</tr>
<tr>
<td>19 April 1971</td>
<td>20 April 1977</td>
</tr>
<tr>
<td>6 May 1971</td>
<td>5 April 1978</td>
</tr>
<tr>
<td>24 May 1973</td>
<td>2 May 1979</td>
</tr>
<tr>
<td>16 June 1973</td>
<td>8 June 1979</td>
</tr>
<tr>
<td>24 April 1975</td>
<td>22 April 1981</td>
</tr>
<tr>
<td>22 May 1976</td>
<td>28 April 1981</td>
</tr>
<tr>
<td>30 May 1976</td>
<td>23 May 1981</td>
</tr>
<tr>
<td><strong>Back-building squall lines</strong></td>
<td></td>
</tr>
<tr>
<td>9 May 1971</td>
<td>17 April 1978</td>
</tr>
<tr>
<td>18 May 1971</td>
<td>22 April 1978</td>
</tr>
<tr>
<td>14 April 1972</td>
<td>11 May 1978</td>
</tr>
<tr>
<td>30 April 1972</td>
<td>9 May 1979</td>
</tr>
<tr>
<td>30 May 1974</td>
<td>3 April 1981</td>
</tr>
<tr>
<td>8 June 1974</td>
<td>13 May 1981</td>
</tr>
<tr>
<td>1 April 1977</td>
<td></td>
</tr>
<tr>
<td><strong>Broken-areal squall lines</strong></td>
<td></td>
</tr>
<tr>
<td>26 May 1971</td>
<td>29 April 1972</td>
</tr>
<tr>
<td>31 May 1971</td>
<td>6 May 1973</td>
</tr>
<tr>
<td>2 June 1971</td>
<td>21 June 1978</td>
</tr>
<tr>
<td>7 June 1971</td>
<td>6 June 1979</td>
</tr>
<tr>
<td><strong>Embedded-areal squall lines</strong></td>
<td></td>
</tr>
<tr>
<td>19 April 1972</td>
<td>28 May 1980</td>
</tr>
<tr>
<td>7 April 1975</td>
<td>1 June 1981</td>
</tr>
<tr>
<td>17 May 1980</td>
<td></td>
</tr>
<tr>
<td><strong>Isolated supercells</strong></td>
<td></td>
</tr>
<tr>
<td>16 April 1967</td>
<td>29 May 1976</td>
</tr>
<tr>
<td>19 April 1972</td>
<td>20 May 1977</td>
</tr>
<tr>
<td>24 May 1973</td>
<td>17 May 1981</td>
</tr>
<tr>
<td>20 April 1974</td>
<td>22 May 1981</td>
</tr>
<tr>
<td>8 June 1974</td>
<td></td>
</tr>
</tbody>
</table>

* See Bluestein and Parks (1983) for a complete list of references for these cases.

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2 Not to be confused with, appropriately, a character in *The Tempest*. 

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**Fig. 1.** Idealized depiction of squall-line formation.
occurs on a time scale of 20–30 min and can take place repeatedly for as long as six hours. Evidence that our classification scheme (which is based solely on radar data) is valid is found from cluster analysis of other types of data and is discussed briefly in Section 4.

The distribution of type of severe, convective-line

Fig. 2. Example of broken-line development as seen on the NSSL WSR-57 radar PPI display on 5 April 1978; range markings are at 40-km intervals; (a) 2350 GMT, (b) 2355 GMT, (c) 0020 GMT (6 April).

Fig. 3. Example of back-building development on 11 May 1978; as in Fig. 1, except that range markings are at 100-km intervals; (a) 0108 GMT (12 May), (b) 0125 GMT, (c) 0132 GMT.
However, these findings cannot be generalized because the sample size is too small for them to be statistically significant.

Consideration was given to the range dependence of minimum detectable height and of resolution. The ra-

Fig. 4. Example of broken-area development on 6 June 1979; as in Fig. 1; (a) 2100 GMT, (b) 2130 GMT, (c) 2215 GMT.

Fig. 5. Example of embedded-area development on 7 April 1975; as in Fig. 1; (a) 2300 GMT, (b) 2345 GMT, (c) 0030 GMT (8 April).
Table 2. Distribution of type of severe convective-line formation (1971-81).

<table>
<thead>
<tr>
<th>Type of line formation</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broken line</td>
<td>6</td>
<td>6</td>
<td>2 (2.75)(^a)</td>
<td>14 (14.75)</td>
</tr>
<tr>
<td>Back-building</td>
<td>6</td>
<td>6</td>
<td>2 (2.75)</td>
<td>14 (14.75)</td>
</tr>
<tr>
<td>Broken areal</td>
<td>1</td>
<td>3</td>
<td>4 (5.5)</td>
<td>8 (9.5)</td>
</tr>
<tr>
<td>Embedded areal</td>
<td>2</td>
<td>2</td>
<td>2 (2.75)</td>
<td>6 (6.75)</td>
</tr>
<tr>
<td>Other</td>
<td>4</td>
<td>4</td>
<td>2 (2.75)</td>
<td>10 (10.75)</td>
</tr>
<tr>
<td>Total</td>
<td>19</td>
<td>21</td>
<td>12 (16.5)</td>
<td>52 (56.5)</td>
</tr>
</tbody>
</table>

\(^a\) Quantities shown in parentheses include adjustments to the tabulations because the radar was shut down from mid-June during 6 seasons.

dar’s low-elevation angle view of squall-line formation at long range is at a higher altitude than at short range. It is therefore possible that “new” echoes could appear at low elevation angles as a line of shallow precipitation elements moves closer to the radar. However, for a line speed of 15 m s\(^{-1}\) at a range of 200 km at a 0.5° elevation angle, the center of the radar beam following the line drops only 200 m in 30 min. It is unlikely that such a small vertical change occurring on the typical time scale of squall-line development would result in the mistaken identification of line formation. In addition, most lines formed within a range of 200 km, where the radar-beam resolution is fine enough to detect the appearance of new cells.

3. Satellite observations of squall-line formation

We looked at sequences of visible satellite photographs to see which, if any, of the types of radar-observed squall-line formation may be discerned independent of the radar before the formation of precipitation. An example of broken-line formation is shown in Fig. 6 for the same radar-observed case shown in Fig. 2. Cumulus and cumulus congestus clouds form at nearly the same time along a band in northwestern Oklahoma (2131 GMT), and individual cumulonimbus elements grow within the band (2231 and 2301 GMT) as it moves eastward. Satellite-observed broken-line formation appears earlier than the radar observed formation before detectable precipitation has been formed.

Figure 7 shows the same example of back building displayed in Fig. 3. Before precipitation has been detected by the NSSL radar, a short (approximately 100 km) line segment of cumulus congestus appears on the Oklahoma-Kansas border (1931 GMT). New cumulus elements appear on the southwestern side of the line segment, while anvil blowoff from cumulonimbus clouds streams off toward the northeast (2031 GMT). The 2101 GMT satellite photograph shows a thin line of cumulus congestus in north-central Oklahoma with a well-defined transition to cumulonimbus to the northeast. In Fig. 8 we see a storm-intercept photograph of a new cumulonimbus element forming at 2127 GMT to the southwest of the thin line of cumulus congestus shown in the 2101 GMT satellite photograph (camera location at 2127 GMT indicated by circle). This cumulonimbus developed, moved northeastward and merged with the older storms along the Oklahoma-Kansas border. The cyclical nature of backbuilding is illustrated further in a later sequence of infrared satellite photographs (Fig. 9) which cover the same time period shown in the radar sequences of Fig. 3. The southwestern edge of the squall line in northeast Oklahoma (0032 GMT) moves eastward, and by 0101 GMT a thin line of clouds appears on the southwestern side. By 0201 GMT, the squall line has in effect extended itself southwestward. An after-sunset storm-intercept photograph of the southwestern edge of the line, taken between 0136 and 0203 GMT, shows the anvil at the top and the flanking line of cumulus congestus (indicated by arrow) which marks the southwestern extremity of the squall line (Fig. 10). With time, the squall line was observed to extend itself even further southwestward as a result of new cloud growth.

The satellite-observed broken-areal formation corresponding to the radar-observed formation seen in Fig. 4 is shown in Fig. 11. At 1932 GMT a 100-km wide band of cumulus, cumulus congestus and small cumulonimbus clouds extends from southwestern Oklahoma across central Oklahoma into northeastern Oklahoma. Several areas of cumulonimbus clouds are scattered within this band at 2002 GMT, as evidenced by the appearance of small anvils. The cluster of cumulonimbus clouds in extreme southwestern Oklahoma at 2032 GMT (indicated by arrow) corresponds to the cluster of radar echoes shown in Fig. 4 that turns into a squall line to the west and southwest of Norman. The actual transformation of the cluster of echoes into a squall line between 2100 and 2215 GMT is not seen in the corresponding sequence of visible satellite photographs (not shown) because anvils from earlier convective activity obscure any new cumulus towers which may be growing below. It is possible that the broken-areal process can be discerned in enhanced infrared satellite imagery. However, further investigation of this is beyond the scope of our study.

Like broken-areal formation, embedded-areal formation is also not easily seen in sequences of visible satellite photographs due to obscuration by clouds. Figure 12 shows a satellite photograph of a squall line whose radar depiction is seen in Fig. 5. Although the back edge (western side) of the squall line is brightly illuminated by the setting sun, there was no evidence of the growth of an intense line within the squall-line associated cloud mass. Like the broken-areal process, the embedded-areal process might also be discerned in enhanced infrared imagery, though we made no attempt to confirm this.
4. Analysis of surface and upper-air data

Regional surface maps based upon hourly data from the National Weather Service (NWS) observation network (including military and automated stations) were analyzed for the time period several hours prior to squall-line formation up until the mature stage of the line. Data were unavailable for 3 of the 40 cases. In 11 of 13 cases, broken-line formation occurred along and within 70 km of a surface cold front. Back-building formation was observed with roughly identical frequency in advance of a dryline (4 cases), along a cold front (3 cases) and at the intersection of a dryline and a front (3 cases); occasionally it occurred at the intersection of a cold front and a thermal boundary (2 cases). Broken-areal formation was documented along and within 90 km of a quasi-stationary front (3 cases) and 80–200 km east of a dryline (4 cases). Since only 5 cases of embedded-areal formation were documented, and they occurred in four different synoptic and mesoscale settings, no conclusions can be drawn concern-
Fig. 8. Photograph of the development of a cumulonimbus just to the southwest of the squall line at 2127 GMT, 11 May 1978, north of Garber, OK; looking to the southwest (NSSL photograph by Howard B. Bluestein).

ing the relationship between embedded-areal formation and surface features.

Using techniques similar to those of Bluestein and Parks (1983), we constructed representative soundings from rawinsonde data from the standard NWS synoptic network [gleaned from archives at the University of Oklahoma (OU), NSSL and the National Climatic Center (NCC)], from special soundings released at nonstandard times in the NSSL mesoscale rawinsonde network (Barnes et al., 1971), and from the hourly surface analyses. Soundings that, based on the radar-echo distribution and surface reports, appeared to be contaminated by convection or that sampled an air mass that was not representative of the inflow region of the squall line (e.g., at low-levels on the dry side of a dryline or on the cool side of an outflow boundary) were not used, since our objective was to determine the undisturbed squall-line environment. Upper-air analyses at mandatory levels were used to see if the approximated sounding differed significantly from the large-scale environment. Soundings and surface data were linearly interpolated with respect to time and space when it was appropriate. A technique devised by Inman (1970) and used by Mogil and Bonner (1971), Steyaert and Darkow (1973) and Darkow and Tansey (1982) was used to account for variations in the low-level moisture field. This technique is based on the assumption that the moisture profile in a shallow layer near the ground is a function of the surface dew-point. The pressure-weighted water vapor mixing ratio in the lowest 50 or 100 mb was estimated from nearby surface mixing ratios and from the ratio of the pressure-weighted mixing ratio in the lowest 50 or 100 mb to the surface mixing ratio at nearby rawinsonde stations, mainly after late morning when the nocturnal inversion had been de-

Fig. 9. As in Fig. 7 but a sequence (see Fig. 3) of infrared satellite photographs: (a) 0032 GMT, (b) 0101 GMT, (c) 0201 GMT. Southwestern edge of squall line where cumulus congestus clouds were forming and growing is indicated by arrows.
Some features are common to all types of storms. The magnitude of the pressure-weighted vertical wind shear vector is largest in the subcloud layer (i.e., below the LCL). The vertical shear vector veers with height substantially (i.e., the hodograph is curved sharply) in the subcloud layer, and backs slightly with height aloft. The tropospheric humidity (ratio of precipitable water to saturation precipitable water) has been shown to be a good measure of the amount of vertically integrated water vapor in a column of air because it is relatively insensitive to layers of high relative humidity aloft in which the absolute amount of water vapor is low (Bluestein and Parks, 1983). Thus, if a rawinsonde passes through an anvil or an isolated patch of middle-level clouds, the measure of the environmental moisture content is not biased on the high side. The overall moisture content as indicated by the tropospheric humidity and the precipitable water is essentially the same for all types of storms.

The convective inhibition (CIN; Colby, 1983) is the net work per unit mass required to lift a negatively buoyant air parcel from the surface to the level of free convection (LFC), i.e., the “negative area” under the curve defined by the parcel’s temperature as a function of height. It is given by

$$\text{CIN} = -\int_{z_0}^{z_1} g \left( \frac{\theta_e - \theta_{env}}{\theta_{env}} \right) dz,$$

where $\theta_e$ is the potential temperature of an air parcel having been lifted from the surface ($z_0$) up to the LFC ($z_1$), and $\theta_{env}$ is the potential temperature of the unsaturated environment. The convective available potential energy (CAPE; Moncrieff and Miller, 1976; Weisman and Klemp, 1982) is the net work per unit mass done by the environment on an air parcel (energy per unit mass gained by the air parcel) which rises from the LFC to the equilibrium level (lowest level of zero potential temperature excess above the LFC), i.e., the “positive area” under the curve defined by the parcel’s temperature as a function of height. It is given by

$$\text{CAPE} = \int_{z_1}^{z_2} g \left( \frac{\theta_e - \theta_{env}}{\theta_{env}} \right) dz,$$

where $z_2$ is the equilibrium level. The CIN is a measure of the low-level thermodynamic stability, while the CAPE is a measure of the potential instability at middle and upper levels. Using results from the $t$-test (Fergu-

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3 The properties of the isolated supercells listed here are slightly different from those given in Bluestein and Parks (1983) for the identical storms because 1) the computations in this study were made with a much finer vertical resolution; and 2) different algorithms were used to determine the temperature and moisture content of the low-level air sample which was lifted to its condensation level (LCL) and beyond.

4 The LFC was determined by lifting from the surface an air parcel having the potential temperature and mixing ratio weighted by pressure over the lowest 500 m.
where \((\cdot)_6\) and \((\cdot)_{0.5}\) represent pressure-weighted means over the lowest 6 and 0.5 km. Weisman and Klemp (1982) found observational and numerical evidence that low values of Ri (roughly between 15 and 35) favor the development of supercells, while high values of Ri (larger than 40) favor the development of multicell storms. Our results show that the average Ri for broken-line storms is large (111) like multicell storms, while the average Ri for back builders is small (32) like isolated supercells (33). Since the values of CAPE in the environment of back-building storms (2090 \(m^2 s^{-2}\)), isolated supercells (2490 \(m^2 s^{-2}\)) and broken-line storms (2820 \(m^2 s^{-2}\)) are not significantly different (not at the 95% level or better), the lower values of Ri in the case of back-building and supercell storms are due to the greater vertical shear.

The relative helicity \((H; Lilly, 1983)\) is the normalized component of the storm-relative wind in the direction of the curl of the storm-relative wind field. It is given by

\[
H = \frac{(V - V_c) \cdot [\nabla \times (V - V_c)]}{|V - V_c||\nabla \times (V - V_c)|},
\]

where \(V_c\) is the storm-motion vector. The storm-motion vector is obtained from cell motion computed from sequences of radar photographs early in the life of the squall line. It is possible later on that cell motion changes or becomes more difficult to determine. In computing (4) we neglect the vertical component of the curl (vorticity), since away from tornadoes and mesocyclones it is much less than the horizontal component of the curl (vertical shear), while the horizontal motions and vertical motions are approximately equal in magnitude. In other words, the relative helicity is large when the storm-relative wind is perpendicular to

\[
\text{Fig. 11. Example of broken-areal development on 6 June 1979 (see Fig. 4); as in Fig. 6: (a) 1932 GMT, (b) 2002 GMT, (c) 2032 GMT.}
\]

\[
\text{Fig. 12. Example of embedded-areal development on 0000 GMT, 8 April 1975 (see Fig. 5); as in Fig. 6.}
\]
the hodograph. It is thus a measure of the combined effect of wind speed and rate of change of wind shear direction with height in a coordinate system moving with the storm. Lilly (1983), using an argument based on the properties of turbulence, hypothesized that low values of $H$ are associated with short-lived cells, while high values of $H$ are associated with longer-lasting cells. Table 3 shows the pressure-weighted tropospheric mean values of relative helicity ($\tilde{H}$). Broken-line storms are characterized by small $\tilde{H}$ (0.07), while back-builders (0.34) and isolated supercells (0.39) are characterized by large $\tilde{H}$; the difference in $\tilde{H}$ between the latter two and former categories is better than the 99% confidence level.

Until now we have discussed the averages of properties of individual wind and thermodynamic soundings. We shall now discuss the properties of averaged soundings. The characteristics of the averaged soundings for each class must be interpreted with caution because of the small sample size. Composite hodographs for squall lines and isolated supercells are shown in Fig. 13. These hodographs were constructed from averages of winds within each class. The broken-line hodograph has the same general shape as the back-builder and supercell hodographs; the weaker shear, however, is evident as the hodograph looks “smaller.” Each squall-line hodograph was also plotted in a reference frame moving in the +x-direction with the squall line; each squall line is oriented along the y-axis. In this coordinate system the $u$-component of the wind represents relative flow normal to the squall line and in the direction of squall line motion, while the $v$-component of the wind represents relative flow along the squall line. The composite hodographs shown in Fig. 14 were obtained by averaging these individually rotated hodographs. Comparing Fig. 14 to Fig. 13, we see that each category of squall-line hodograph in Fig. 14 looks remarkably like the corresponding one in Fig. 13 rotated in a counterclockwise direction. Thus, there is a systematic relationship between orientation of the vertical-shear vector and orientation of the squall line. Otherwise, Fig. 14 would not have the same shape as Fig. 13. At each level the difference between orientation of the squall line and the vertical shear vector is given by the angle formed between the $v$-axis and a line tangent to the hodograph. Figure 14 thus shows that each type of line is oriented along the shear in the lowest 1 km MSL. Broken-line and back-building squall lines are perpendicular to the shear somewhere roughly between 1.8 and 2 km MSL, and at an angle of roughly 30–40 deg between 3 and 7 km MSL. Broken-areal and embedded-area hodographs are perpendicular to the shear over a deeper layer, from approximately 1.8 to 5 km MSL. The composite hodograph for all lines shows that squall lines in general are oriented along the shear in the lowest 1 km MSL, approximately 75 deg from the shear between 1.4 and 3 km and 40 deg above 3 km. If the winds near 3 km MSL are geostrophic, then our composite is consistent with the findings of Byers and Braham (1949, p. 126, Fig. 110). Weighted by pressure throughout the troposphere, or only the lowest 6 km, the vertical shear vector is ori-
ent 40 deg from the line. In the subcloud layer it is roughly 30 deg from the line, while in the cloud layer it is 45 deg from the line.

Only the broken-line composite hodograph shows that a steering level (critical level, at 3.2 km MSL) exists with respect to cell motion, i.e., a level at which the cell is moving along with the wind. The low values of relative helicity associated with broken-line storms are indirectly due to the low wind speeds relative to cell motion. The cell-motion vectors for the other categories of line formation are at least 2.5 m s\(^{-1}\) different from the environmental winds at all levels. If we assume
that squall lines move normal to themselves, then squall-line motion is due to the components of cell motion and discrete propagation normal to the line. The cell motion itself is a result of the wind and continuous propagation. The relationship among the cell-motion vector, wind vector at some height, continuous-propagation vector at some height and the discrete line-propagation vector is depicted in Fig. 15. In the continuous-propagation process, the cell can be tracked as an entity on time scales of minutes; in the discrete line-propagation process, new cells form just ahead of or behind the line. The effect of continuous cell propagation, i.e., the difference between cell motion and the wind, is greatest (minimum of 7.5 m s$^{-1}$ at 2 km MSL in the direction opposite to the flow at the surface) for the back-building lines. The effect of continuous cell propagation is also large (minimum of 8.8 m s$^{-1}$ at 2.8 km MSL in the direction opposite to the flow at the surface) for isolated supercells. The effect of discrete line-propagation, i.e., the difference between line motion and the component of cell motion normal to the line, is from the rear to the front of the line in all cases except the backbuilding case, in which the component of cell motion normal to the line is the same as line motion (Fig. 13). The effect of discrete line propagation is greatest for the broken-line case, in which the discrete line-propagation vector has a magnitude of about 2–3 m s$^{-1}$. Thus, new cells forming ahead of the line contribute to line motion. Cell motion relative to the squall line is mostly along the line with a front-to-rear component of approximately 2 m s$^{-1}$. The latter finding is consistent with Houze and Hobbs' (1982) summary of the behavior of midlatitude and tropical squall lines, in that cells form along the leading edge and dissipate toward the rear. Steering levels with respect to line motion in general exist between 6 and 7 km MSL. The flow is from front to rear below the steering level. Only the broken-line category does not show any rear-to-front flow above the steering level of the line. Figures 13 and 14 show that the wind relative to cell motion generally veers with height. It is weakest between 2 and 5 km MSL.

The variation in the composite hodographs as a function of height and among the different composites may be inferred from Fig. 16. In general, the standard deviation of the along-the-line component of the wind with respect to the mean from each class ($\sigma_u$) increases with height from several m s$^{-1}$ at the surface to 10–15 m s$^{-1}$ near the tropopause. In other words, the boundary layer is relatively uniform in structure from case to case, while the structure of the middle and upper troposphere can vary substantially. Some of the increase in variability with height is due to instrument error. Overall, the variations in the along-the-line component of the wind (represented by its standard deviation $\sigma_u$) are greater than the variations in the crossline component of the wind ($\sigma_v$). This is especially true above 2 km MSL for the back-building and broken-areal cases. An interesting characteristic of $\sigma_u$ is that it has a local maximum near 1–2 km MSL. This level is near the location in the hodograph where the transition is made from sharp curvature (below) to very weak curvature (aloft), and the local maximum in $\sigma_u$ may thus be due to the vertical variation of the height at which this transition occurs. The transition height is approximately the height of the top of the mixed layer.

For the supercell cases the standard deviation of the winds also increases from several m s$^{-1}$ at the surface to 10 m s$^{-1}$ near the tropopause. (However, because the actual supercell hodographs have not been transformed into another coordinate system, we cannot compare $\sigma_u$ and $\sigma_v$ to those from the line cases.)

All the composite soundings displayed in Fig. 17 are conditionally unstable nearly everywhere in the troposphere. The positive area above the LFC in the embedded-areal composite is markedly less than that
Fig. 14. Composite hodographs in coordinate system moving along with the line (squall-line coordinates).
The supercell composite has a maximum $\sigma_T$ of just under 4 deg at 700 mb, while elsewhere $\sigma_T$ is on the order of 2–3 deg.

The vertical variation in the case-to-case variation in dewpoint behaves differently from the temperature variation. Variations in the dew point (measured by its standard deviation $\sigma_{TD}$) in general increase with height. However, $\sigma_{TD}$ has a local maximum at 900 mb in the embedded-areal composite. Thus, with the exception of the embedded-areal cases, the dew point in the boundary layer is relatively uniform from case to case, while aloft it varies more substantially. The rapid increase of $\sigma_{TD}$ with height for backbuilders, with a local maximum at 850 mb, may be due to variations in the height of the top of the mixed layer, above which it is dry, and below which it is moist. However, the same variation in dew point aloft as at low levels actually represents a smaller variation in water vapor mixing-ratio. Consequently the large $\sigma_{TD}$ aloft is really not that significant in terms of actual moisture content.

The analysis of the surface and upper-air data for the composites was based on an independent examination and classification of radar-echo formation. Evidence that there is merit to this procedure is obtained by first classifying squall-line type based on the surface and upper-air data, and then seeing how the corresponding cases of radar-observed formation group together. Details on the method of cluster analysis are found in Anderberg (1973) and Gordon (1981). Cluster analysis was performed using the IBM Statistical Analysis System package on variables such as shear, relative helicity, Ri, and CAPE. In 4 of 15 clusters, 6 broken line and broken-areal cases only were grouped; in 2 other clusters, 10 of these cases made up the majority of the group. In another 4 of the 15 clusters, only 4 back-building cases were grouped; in 1 other cluster, 5 of the latter comprised the majority of the group. Therefore, 16 out of 22 broken line and broken-areal cases were clustered, and 9 out of 13 backbuilding cases were clustered; i.e., roughly 70 percent of these cases were either grouped by themselves or comprised the majority of the group. The analysis thus produced clusters in two main groups: 1) back-builders and 2) broken-line and broken-areal storms. Although the clusters were not composed exclusively of the same types of lines, and the results depended to some extent on the number of clusters sought, we interpret our results as some objective support for the classification scheme.

5. Discussion

In this section we will discuss how our findings detailed in Sections 2 and 3 relate to other radar studies, to numerical model simulations and to theoretical work. By doing so we hope to broaden the applicability of our results.

In a study of tornadic storms in the midwest from 1955–57, Bigler and Inman (1958) found that many
Fig. 16. Vertical profile of the standard deviation (σ) of the u-component (solid line) and v-component (dashed line) of the wind in squall-line coordinates (except for supercells) for each composite.
Fig. 17. Composite soundings plotted on skew $T$–log $p$ diagrams; temperature (solid line); dew point (dashed line); path in ($T$, $p$) space taken by surface parcel as it ascends (dotted line); pressure plotted in mb on ordinate; temperature plotted on skewed abscissa in °C.
Fig. 18. Vertical profile of the standard deviation ($\sigma$) of temperature (solid line) and dew point (dashed line) for each composite.
of the storms were associated with lines of radar echoes. Although they did not focus on the formation of the lines, some inferences can be made as to how their classification relates to ours. For example, they identified narrow echo lines, 8 out of 9 which were oriented along a cold front, and which sometimes appeared solid early in their life. Houze and Hobbs (1982), in their summary of observational studies of rainbands in extratropical cyclones in the Pacific Northwest, the United Kingdom and the northeastern United States, discussed a similar phenomenon named the narrow cold-frontal band (Houze et al., 1976). The cellular structure of this type of band has been discussed by Hobbs and Biswas (1979). The broken-line squall lines which form along cold fronts are probably specimens of Bigler and Inman’s narrow echo line (which is less than 10 km in width), and intense specimens of Houze et al.’s narrow cold-frontal band (which is approximately 5 km in width). [Compare Fig. 2 to Fig. 1 (top section) in Hobbs and Biswas, 1979, and Fig. 1 to Fig. 3 (0508–0626) in Hobbs and Biswas, 1979.]

Wilhelmson and Klemp (1983) have in effect simulated the beginning of the broken-line process numerically by “growing” a line of periodic convective bubbles spaced 40 km apart. However, there was no line of forcing as there is along a cold front. They found that the subsequent behavior of the storms as they interacted with their neighbors depended on the environmental wind shear profile and its relationship to the orientation of the line of forcing. The environmental shear was sufficiently strong in their simulations so that supercells or lines of supercells formed, and broken-line formation did not occur.

Newton (1963) suggested that when a band of forced ascent along a front is oriented at an angle to a tongue of potential instability, a back-building process can occur as the cold front overtakes the instability tongue at locations successively farther south. Our observations indicate, however, that back-building can occur along a dryline even when it is not overtaking an instability tongue at locations successively farther south. The back-building behavior in this instance may be a consequence of the latitudinal variation in strength of the low-level inversion which caps the moist layer; if the inversion is stronger to the south, then the time at which convective temperature is reached along the dryline due to daytime heating is later to the south, where more CIN must be overcome.

The growth in areal extent of a mesoscale convective system from a small convective element was noted by Fujita and Brown (1958), Wilhelmson and Klemp (1981) and Klemp and Weisman (1983) numerically simulated this phenomenon in that they produced a squall line from a single cell in the absence of mesoscale forcing. Klemp and Weisman (1983) demonstrated how the organizational character of a mesoscale convective system from a single cell depends upon the vertical-shear profile. In a case in which the vertical-shear vector turns 180 deg in and is confined to the lowest 5 km, a single cell develops into a configuration in which there is a supercell located at the end of a multicellular line. If the shear vector turns only 90 deg in and is confined to the lowest 2.5 km, a multicellular squall line forms. In none of the cases did a back-building squall line form from one cell as is often observed.

The development of a broken-areal squall line has been numerically simulated to some extent by Wilhelmson and Klemp (1981). Although their simulation began with a single cell, which underwent successive splits, the broken-areal formation process may be regarded as having begun after the initial splits had occurred, when the line developed along the cold outflow boundaries between the existing cells. The splitting process itself has no effect on the broken-areal formation process. Wilhelmson and Chen (1982) demonstrated numerically that cells can in fact be generated over or just behind cold outflow boundaries produced by previous cells.

Houze and Hobbs’ (1982) warm-frontal bands and wide cold-frontal bands, which arise when precipitation is enhanced within a larger area of stratiform precipitation and cloudiness, may be similar to the embedded-areal squall lines. Houze and Hobbs (1982) cite the “seeder-feeder” process, ducted gravity waves (Lindzen and Tung, 1976) and conditional symmetric instability (Bennetts and Hoskins, 1979) as mechanisms which could play a role in producing these bands.

Moncrieff (1981) has proposed a dynamical classification of organized convection which is steady in the moving reference frame of the mesoscale convective system. Since all the composite hodographs have a critical level with respect to squall-line motion, the squall lines in our sample most closely fit the steering-level model (Moncrieff, 1978). It has been argued that this model, which has a downshear sloping updraft, is not thermodynamically consistent in two dimensions. Seitter and Kuo (1983), on the other hand, showed that this model has an upshear-sloping updraft and can be thermodynamically realistic if the effects of precipitation loading are included. The squall-line hodographs all have strong vertical shear below cloud base, and weaker vertical shear aloft (Table 3). Thorpe et al. (1982) showed numerically that this condition also allows a more realistic steady, two-dimensional, upshear-sloping updraft to exist. In any event, our observations show that with the exception of the embedded areal cases, squall lines that appear forming on radar are three-dimensional.

Raymond (1984) suggested that the downshear-propagating disturbances in his wave–CISK model may be interpreted as squall lines. He hypothesizes that squall lines must have a component of propagation down the low to midlevel shear if the shear is strong, and will not be oriented precisely perpendicular to the shear. This is supported by the composite hodographs shown in Fig. 14. For example, in the strongly sheared back-building hodograph, the shear between 2 km MSL and the tropopause is oriented roughly 30 deg from...
the squall line. In the more weakly sheared broken-line hodograph, the shear between 3 km and 7 km MSL is oriented 40 deg from the squall line.

6. Summary and conclusions

The following, four primary modes of radar-observed severe squall-line development occur during the spring in Oklahoma: (i) broken line, (ii) back building, (iii) broken areal, and (iv) embedded areal. The former two occurred more frequently in the season, while broken-areal formations occurred more frequently later in the season. The broken-line and back-building formation processes are easily discerned in visible satellite photographs, but broken-areal and embedded-areal developments are not. However, no attempt was made to see if the latter two processes can be seen in enhanced infrared images.

Most broken-line squall lines form along a cold front and may represent intense examples of the narrow cold-frontal band. Their environment is one of relatively weak vertical shear, large CAPE and large bulk Richardson number; cells within the squall line have low relative helicity. Since a steering level exists for cell motion, the effects of continuous propagation are relatively small. However, there is some discrete line propagation. Broken-line formation is therefore probably the development of multicells “externally” forced by a band of rising motion which may be frontogenetically induced.

Back-building squall lines can occur along a number of different types of surface boundaries. They occur in an environment of strong vertical shear, large CAPE and large Richardson number; cells within the squall line have high relative helicity. The effects of continuous cell propagation are larger than for any other type of squall-line formation, and there is no discrete line propagation. The back-building environment is very similar to that of supercells. It is therefore possible that back-building squall lines may be “internally” forced, since in a supercell environment the local vertical shear initially organizes the structure of convective elements (Rotunno and Klemp, 1982), independently of the “external” mesoscale forcing. However, the influence of external forcing cannot be ruled out.

Broken-areal formation has been to some extent numerically simulated and appears to result from the interaction of outflow boundaries. Squall lines which develop through the embedded-areal process may be examples of the warm-frontal bands and wide cold-frontal bands. They are characterized by relatively low values of CAPE, and are probably due to some hydrodynamic instability in the flow or to ducted gravity waves.

All the squall lines form in a conditionally and convectively unstable atmosphere which is characterized by strong vertical shear and turning of the shear vector with height at low levels, and weaker shear and only slight turning aloft. There is more variability in the environmental hodographs aloft than at low levels. The squall lines are usually oriented along the mean shear in lowest 1 km, at a large angle to the shear in the lower part of the middle troposphere, and at an angle of 30–40 deg from the shear somewhere in the upper troposphere. The squall lines fall into the steering-level category proposed by Moncrieff (1978); each type has a steering level with respect to line motion around 6 or 7 km MSL. Cells tend to move along the line, with a little component against line motion. The absolute moisture content in the environment of each category of squall-line formation is roughly identical.

7. Further discussion

The results of our analyses raise many interesting questions. If back-building squall lines form in a supercell environment, why do isolated supercells occur sometimes, while squall lines develop at other times? We already know that the ways in which cells triggered along a line interact with their neighbors depends on the relationship of the orientation of the line to the vertical shear (Wilhelmson and Klemp, 1983). Since isolated supercells often form along or near surface boundaries (see the references for the supercell storms in Bluestein and Parks, 1983), and since there is a systematic relation between squall-line orientation and the vertical shear, could it be that the relative orientation of the surface boundary to the vertical shear is an important factor? A preliminary attempt was made to test this hypothesis using the observational data base for this study. The average difference in orientation between the pressure-weighted mean shear in the lowest 6 km and the line of forcing (i.e., front, dryline or outflow boundary) was 56 deg (26 deg standard deviation) for back-building squall lines and 63 deg (10 deg standard deviation) for isolated supercells. The difference between back-building squall lines and isolated supercells in terms of the difference in orientation between shear and line of forcing is not statistically significant at the 95 percent level. There are, however, several significant problems in using observations to test the hypothesis: (a) How does one properly interpret measurements of the difference between shear and line-of-forcing orientation, given that the former is a vector, while the latter is not? We considered only the magnitude of the acute angle formed by the shear vector and line of forcing. What about the direction? (b) Sometimes supercells form near the intersection of two boundaries, particularly fronts and drylines. Which boundary should be considered the “line of forcing”? We considered the closer boundary. (c) The orientation of a surface boundary may change with time. At what time should the orientation of the boundary be measured? (d) Suppose the supercell does not form along a line of forcing at all. (There were a number of instances among the broken areal and embedded-areal cases in which the squall line did not form along a preexisting mesoscale or synoptic-scale boundary.) For these cases, the hypothesis is not relevant.
In Fig. 13 we see that climatologically the mean vertical shear in Oklahoma when squall lines and isolated supercells form is westerly or west-southwesterly. The dryline is usually oriented in the north–south direction because of topography (Schaefer, 1974), so that the vertical shear and dryline are usually nearly perpendicular to each other. The authors have observed that cold fronts in Oklahoma, on the other hand, are usually oriented somewhere in between the east–west and northeast–southwest directions, and rarely in the north–south direction. This is because the entrance of fronts into Oklahoma is most often a result of the southward or southeastward motion of a cold anticyclone situated to the north in the lee of the Rockies (Zishka and Smith, 1980). Thus, cold fronts are usually oriented within 45 deg from the shear. Our analyses indicate that when a dryline intersects a front, a squall line tends to form along the front, while isolated supercells occur at the intersection or along the dryline. More observational work and numerical modeling are needed to test our hypothesis. Do isolated supercells form preferentially along one type of boundary, and squall lines along the other, because of the difference in relative orientation of the boundary and the shear? Or is the observed difference in line-mean shear orientation merely a result of the climatological orientations of surface boundaries and the shear, and is therefore not physically important? Furthermore, under what conditions, if any, can squall lines develop from isolated supercells?

Broken-line squall lines form as the spaces in between cells are filled with new cells or the expansion of existing cells. Does the along-the-line component of the cells (Fig. 14) contribute toward filling in the line? Do intersecting outflow boundaries from neighboring cells act to trigger new cells and thereby solidify the line? Does along-the-line advection of moisture and precipitation (Hjelmfelt and Heymsfield, 1981) play a role in line development? Why do cells initially form, rather than a solid line—is it related to a requirement of three-dimensionality?

Our discussion has been based on observations of severe squall line formation in one particular geographical region during a particular season. Do our findings hold elsewhere and during other seasons? Do less intense convective lines behave differently? The latter question will be addressed in a future paper.

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