Convective Dynamics

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Overview

Squall Lines: Introduction

In this section, we will cover

- General characteristics of squall lines
  - organization
  - structure
  - associated weather
- Conceptual models
- Theories of long-lived squall lines

Squall Lines: Definition

A *squall line* is a type of multicell storm that consists of a line of storms with a continuous, well developed gust front at the leading edge of the line.

These storms can produce small to moderate size hail, occasional flash floods and weak tornadoes.

Squall Lines: Definition

Squall lines are bands of precipitation that are at least partly convective.

Frontal rainbands containing only forced precipitation are not considered squall lines

Squall lines can stretch hundreds or even thousands of kilometers in length and last for many hours. They therefore fall into the category of *mesoscale convective system*.

Squall Lines: Conceptual Model

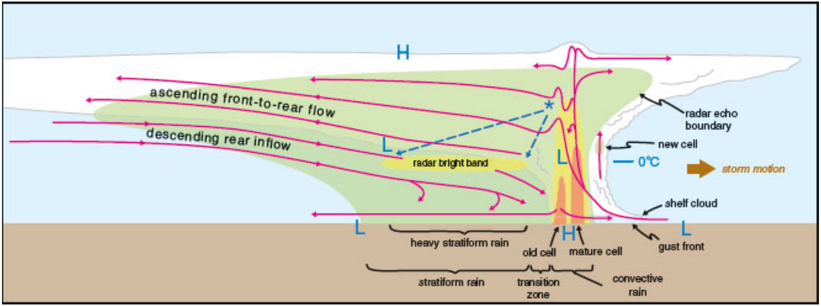


Figure: Conceptual model of a squall line with trailing stratiform area viewed. The green shading indicates the region of precipitation-sized hydrometeors. The yellow and orange shading indicates more intense radar echoes. Pressure minima and maxima are also indicated, as is the height of the melting level, which is located just above the height at which a radar bright band is observed.

Squall Lines: Conceptual Model

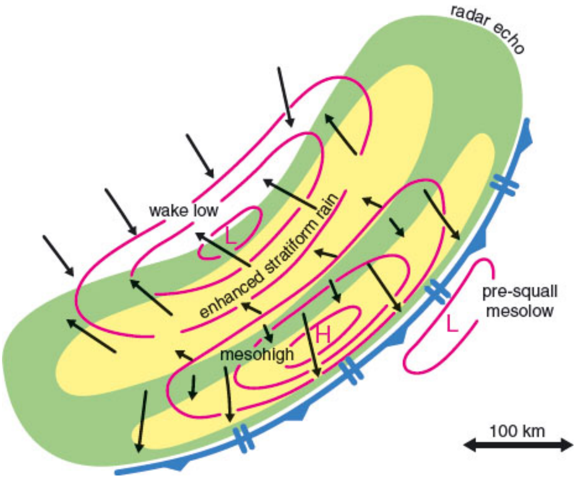


Figure: Schematic surface pressure, wind, and precipitation fields during the mature stage of a squall line. Arrows indicate actual (as opposed to system-relative) winds.

Squall Lines: 2D Features

Squall lines can often be considered *quasi-two-dimensional* systems, with the properties of the individual convective cells and system-scale circulation features quite similar all along the line.

Because of this, much can be learned by studying their circulation as viewed in a two-dimensional vertical cross section taken perpendicular to the line.

Squall Lines: 3D Features

However, there are aspects of squall lines that must be understood in terms of *three-dimensional* flow features.

For instance, when there is sufficient shear to support supercells within the line, each supercellular updraft and downdraft will display significant three-dimensional flow characteristics.

Also, mesoscale vortices often form at the ends of a squall line or at breaks within the line. Such mesoscale vortices are critical to the development of severe bow echoes.

Squall Lines: Radar View

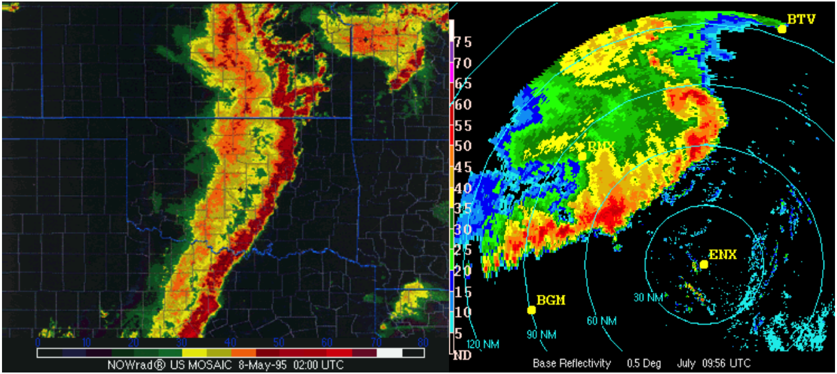
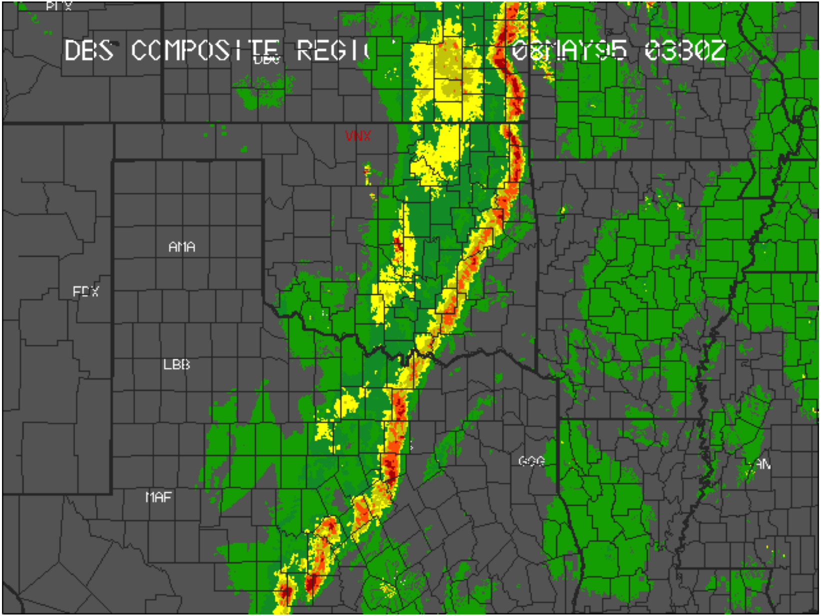
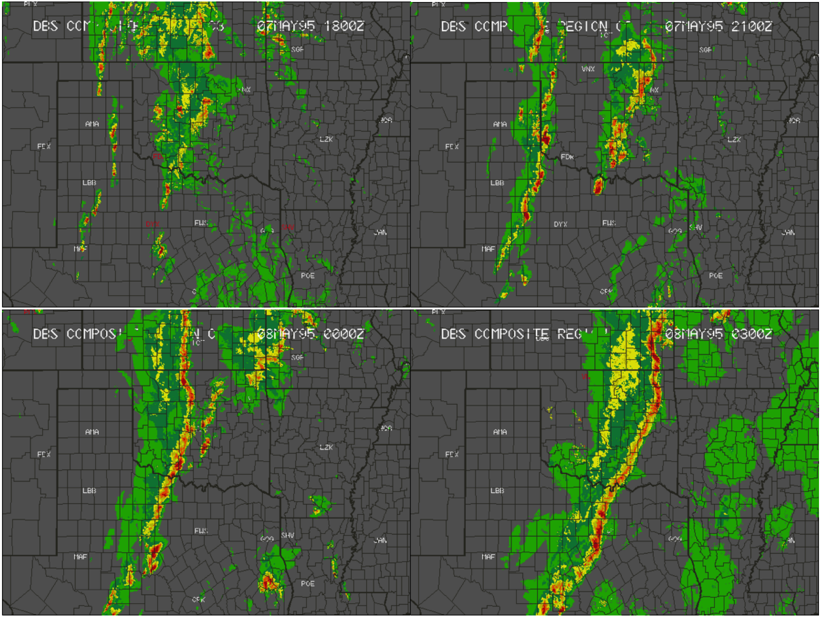


Figure: A primarily 2D system (left) and a system with significant 3D features (right)

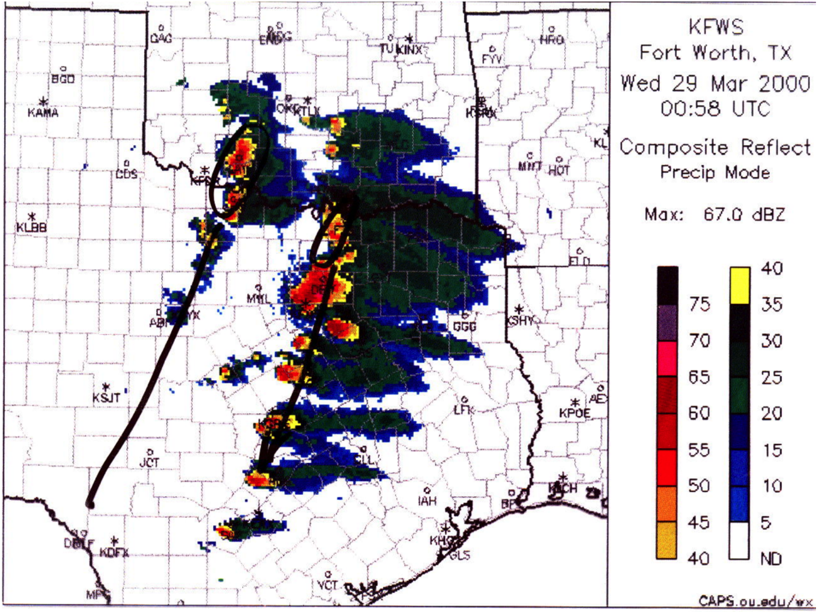
7 May 1995 Squall Line w/Trailing Stratiform Precipitation



7 May 1995 Squall Line w/Trailing Stratiform Precipitation



Squall Lines: Composed of Discrete Thunderstorms



Squall Lines: Formation

- Squall lines form in a variety of ways.
  - They often originate as a scattered line of convective cells, with new cells eventually filling in the holes in the line.
  - They also may be triggered as a nearly solid line to begin with.

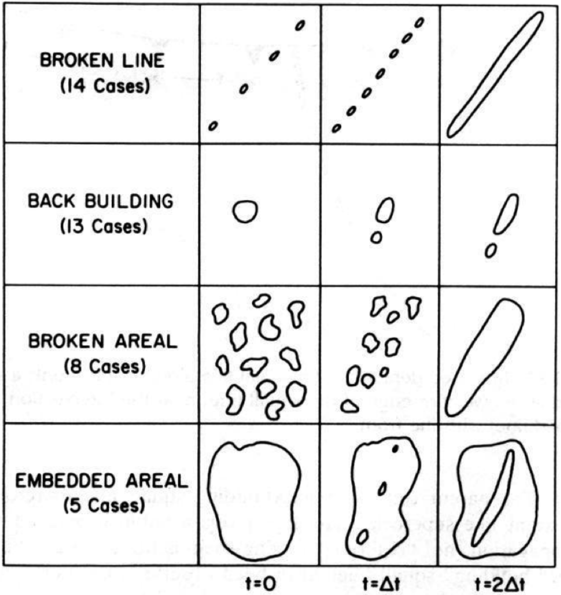
- This latter scenario is especially likely when there is strong large-scale or mesoscale forcing present, as with a cold front or dryline.
- In some cases, squall lines are also observed to form from more scattered regions of convective cells or embedded within a more uniform region of stratiform precipitation.

Squall Lines: Formation

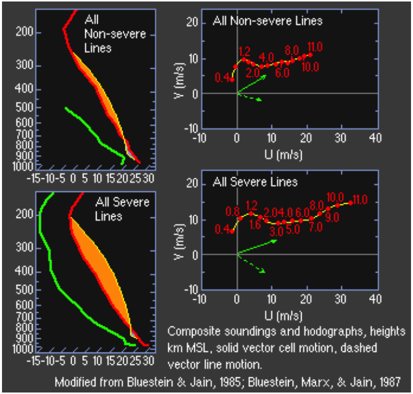
- Bluestein and Jain (1985) classified the modes of severe squall line formation in Oklahoma
  - broken line
  - back-building
  - broken areal
  - embedded areal

- Broken line and back-building cases are the most common forms.

Squall Lines: Formation

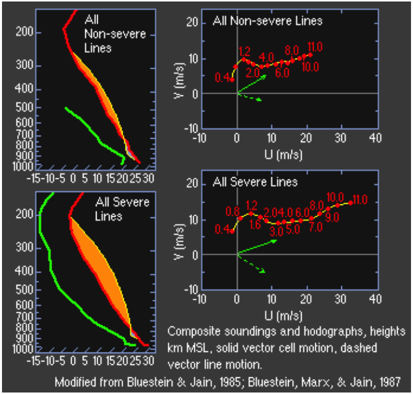


Squall Lines: Composite Sounding and Hodograph



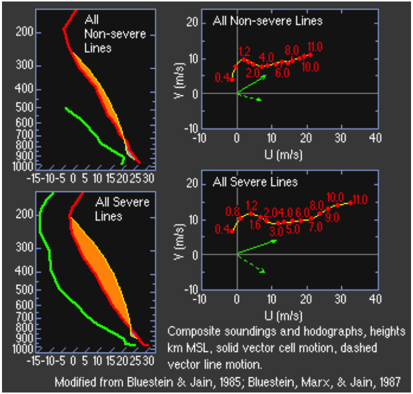
- Squall lines are observed for a wide range of environmental CAPEs and vertical wind shears.
- However, for a given CAPE, strength and longevity of the system increase with increasing depth and strength of vertical wind shear.

Squall Lines: Composite Sounding and Hodograph



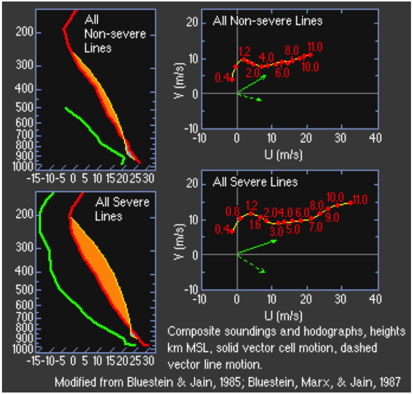
- Bluestein and Jain (1985) and Bluestein, Marx, and Jain (1987) characterized the environments of severe versus non-severe squall lines observed in Oklahoma, classified according to the various modes of squall line formation that they identified.

Squall Lines: Composite Sounding and Hodograph



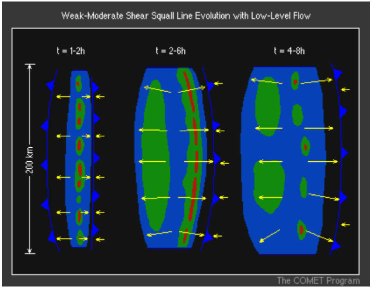
- These studies show that the environments of both severe and non-severe squall lines show significant vertical wind shear, especially at low levels, with the average hodograph oriented about 45 degrees to the line.

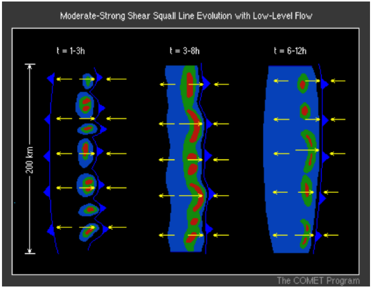
Squall Lines: Composite Sounding and Hodograph



- The magnitude of the shear on average is slightly stronger for the severe lines than for the non-severe lines.
- The average CAPE for the severe lines was significantly larger than for the non-severe lines (2260 $\mathrm{J/kg}$ versus 1372 $\mathrm{J/kg}$).

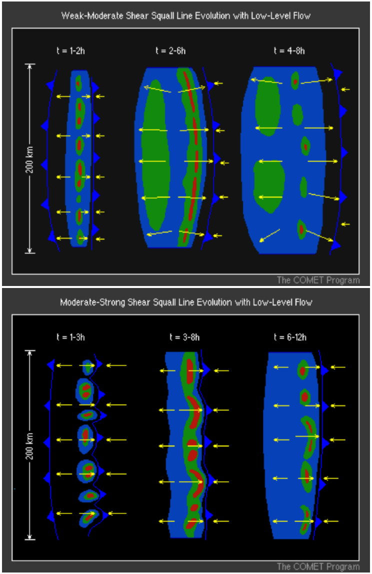
Squall Lines: Low-level Shear





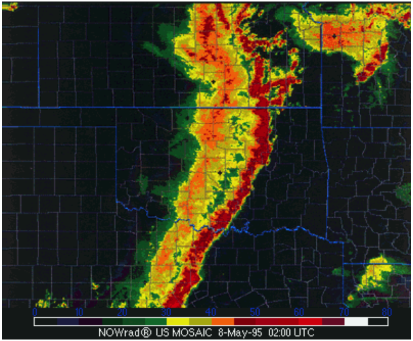
- Once formed, squall lines often display a characteristic lifecycle, starting as a narrow band of intense convective cells and evolving to a broader, weaker system over time.
- However, the time over which this evolution takes place and the specific structures that develop within the squall line depend strongly on the magnitude of the low-level vertical wind shear.

Squall Lines: Low-level Shear



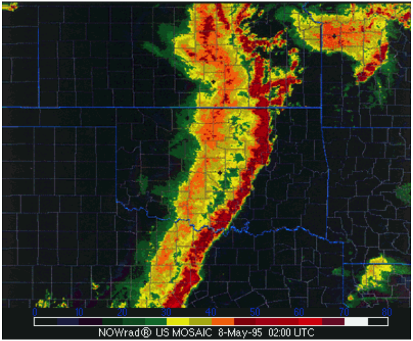
- In general, weak-shear environments produce squall lines that spread quickly upshear and weaken.
- Stronger shear environments produce stronger, more long-lived lines composed of strong, leading line convective cells and, perhaps, bow echoes

Squall Lines: 2D Evolution



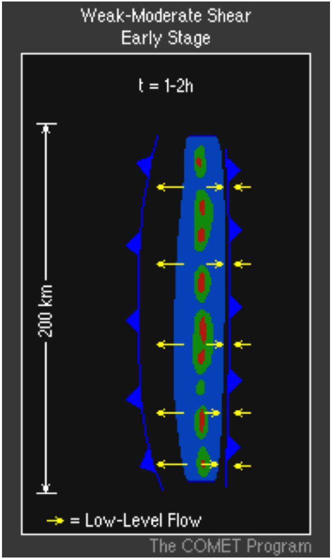
- In presenting the following evolutions, we consider the core region of a squall line, which essentially behaves as a two-dimensional system.
- For longer lines, this evolution is representative of the majority of the entire system.

Squall Lines: 2D Evolution



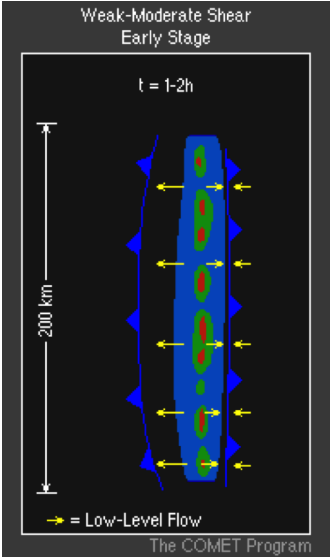
- We will look at the variations to the basic evolution produced by weak-to-moderate and moderate-to-strong shear environments.

Squall Lines: Weak-to-Moderate Shear, Early Stage



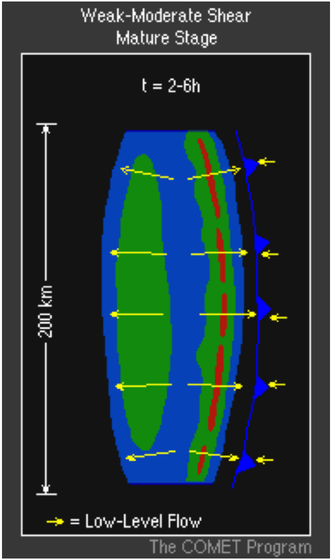
- During the early stages (t=1-2h), the system is composed of mostly independent convective cells, each with its own updraft, downdraft, and cold pool.
- The line often appears quite narrow, with the surface cold pool generally confined to a small region around the convective cells.

Squall Lines: Weak-to-Moderate Shear, Early Stage



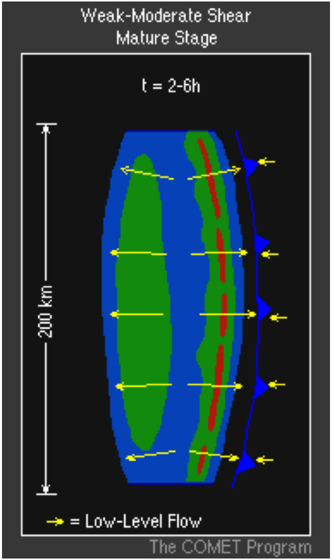
- The surface flow field is characterized by system-relative inflow from the east, with diverging flow evident within the cold pool, and resulting strong low-level convergence along the leading edge of the cold pool, especially in the downshear direction (relative to the low-level shear vector).

Squall Lines: Weak-to-Moderate Shear, Mature Stage



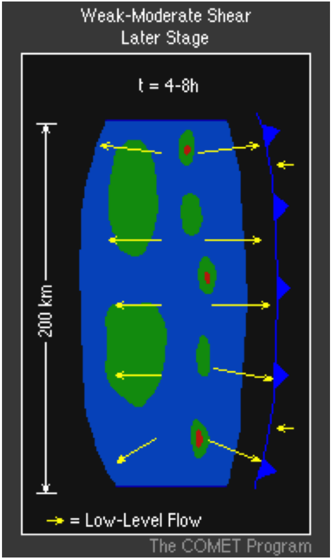
- As the squall line matures (t=2-6h), it develops a mesoscale organization, characterized by a primarily solid line of strong convective cells at the leading edge, with an extensive surface cold pool extending from the leading edge rearward.
- A region of lighter, stratiform precipitation now also extends well to the rear of the leading-line convection.

Squall Lines: Weak-to-Moderate Shear, Mature Stage



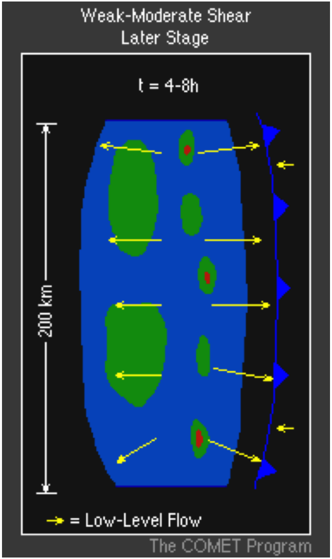
- A narrow region of very light precipitation, referred to as a weak echo channel or transition zone, is often observed between the leading line convection and the stratiform precipitation region.
- The wind field at the surface is characterized by diverging flow within the cold pool and strongly converging flow at the leading edge of the cold pool, especially on its downshear side.

Squall Lines: Weak-to-Moderate Shear, Late Stage



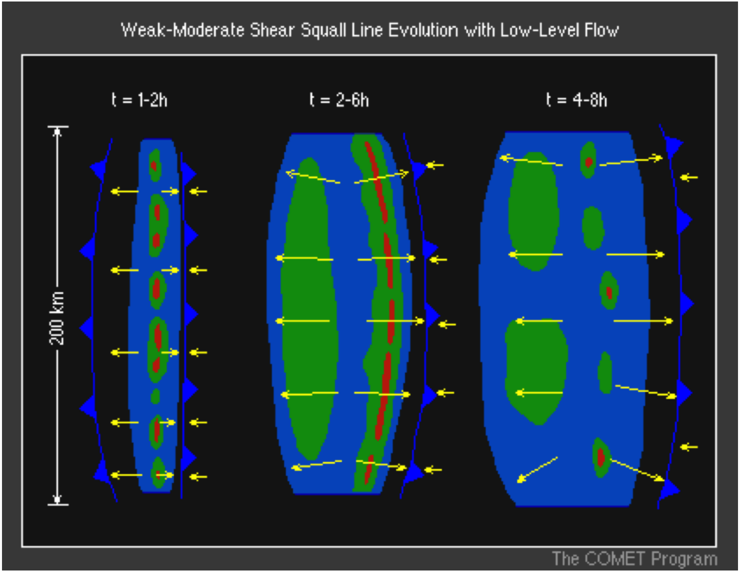
- During the later stage of the squall line (t=4-8h), the leading line convection weakens considerably as the surface cold pool surges well out ahead of the convection.
- The surface flow features are similar to the mature system, but significantly weaker.
- Although the convective cells have weakened, the stratiform precipitation region may last for several hours.

Squall Lines: Weak-to-Moderate Shear, Late Stage

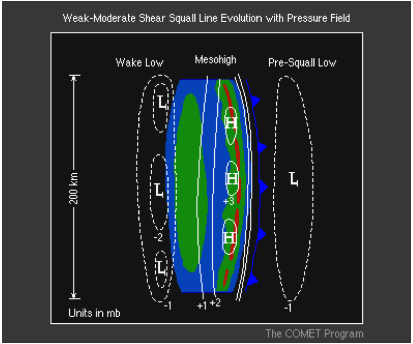


- As the cold pool moves away from the decaying cells, a new line of cells may be triggered as the cold pool weakens, or as the system encounters a more favorable environment.
- The system may then again take on the characteristics of the mature stage and continue its evolution as before. This process has been observed to lengthen the lifetimes of convective systems considerably.

Squall Lines: Weak-to-Moderate Shear, All Stages

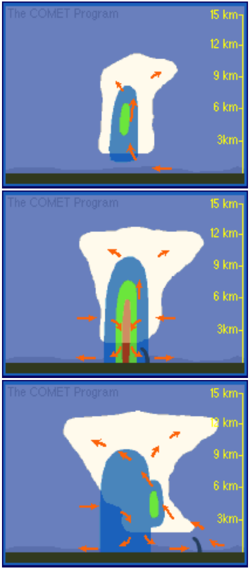


Squall Lines: Weak-to-Moderate Shear, Surface Pressure



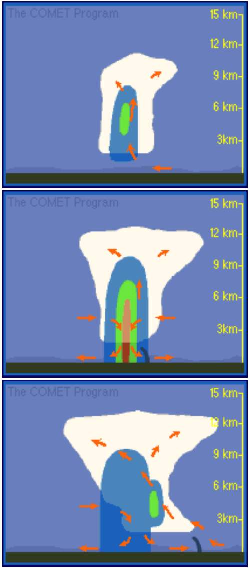
- The surface pressure field during the system's mature phase reveals many of the classic pressure signatures associated with MCSs, including
  - a pre-squall meso-low
  - a meso-high in association with the surface cold pool
  - sometimes a distinct wake low at the back edge of the stratiform precipitation

Squall Lines: Vertical Cross Section, Early Stage



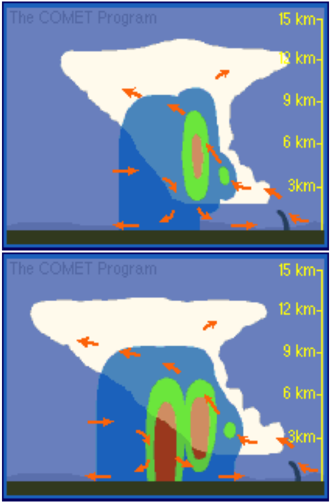
- During the initial stages, a vertical cross section through the interior portion of the line depicts the development of an upright to slightly downshear-tilted convective cell that evolves through a classic lifecycle similar to that of an ordinary cell.
- The flow field is initially characterized by low-level, storm-relative inflow from the east, a strong upright to downshear-tilted updraft, and, finally, an anvil outflow aloft that spreads both westward and eastward, but primarily eastward (given westerly shear).

Squall Lines: Vertical Cross Section, Early Stage



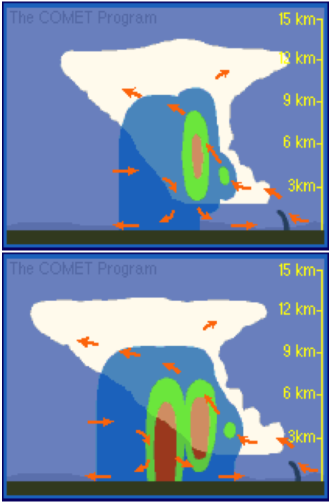
- As the initial cell decays, flow converges into the downdraft at mid-levels from both the front and rear of the system, and then descends and spreads along the surface in the form of a gust front. A new cell is then triggered on the downshear side of the spreading gust front, evolving in a manner similar to the first cell.

Squall Lines: Vertical Cross Section, Mature Stage



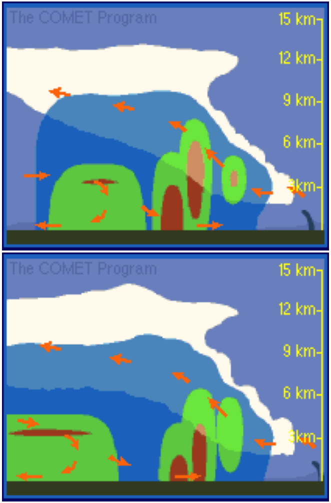
- As the system matures, new cells continue to be triggered along the leading edge of the system. They advect rearward within the system, feeding into an expanding stratiform precipitation region.
- The flow field now contains a well-defined upshear-tilted ascending front-to-rear circulation that exits partially forward, but mostly rearward aloft.

Squall Lines: Vertical Cross Section, Mature Stage



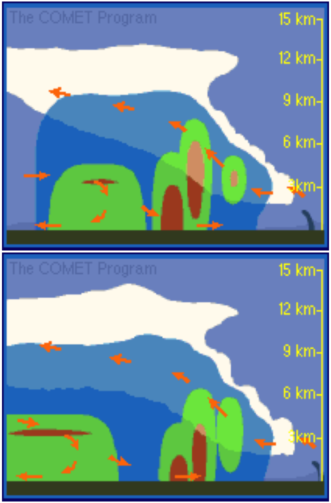
- In addition, it now exhibits a descending rear-to-front current at mid-levels that diverges both forward and rearward when it reaches the surface, within the cold pool. This flow feature is referred to as the rear-inflow jet.

Squall Lines: Vertical Cross Section, Late Stage



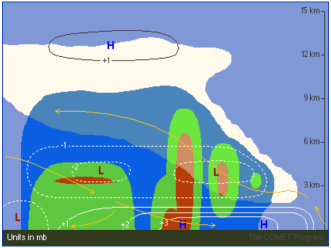
- During the later stage, the leading line of convective cells becomes shallower and weaker as the system tilts even more upshear.
- The flow field becomes characterized by a much shallower front-to-rear ascending current, with the rear-inflow jet descending and spreading along the surface well behind the leading edge of the cold pool.

Squall Lines: Vertical Cross Section, Late Stage



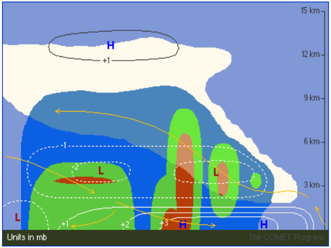
- The surface cold pool often considerably outruns the precipitation region.
- Eventually, the leading line convective cells dissipate completely, leaving behind the stratiform precipitation region.

Squall Lines: Vertical Cross Section, Pressure Field



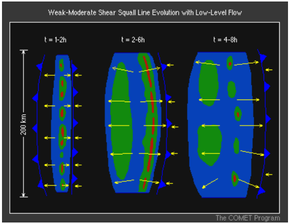
- A vertical cross section of the pressure field during the mature stage depicts a meso-high associated with the cold pool at the surface and a mesolow at mid-levels, extending rearward from just above and behind the top of the cold pool.
- Also depicted is the pre-squall low and wake low at the surface and a mesohigh at the top of the anvil.

Squall Lines: Vertical Cross Section, Pressure Field



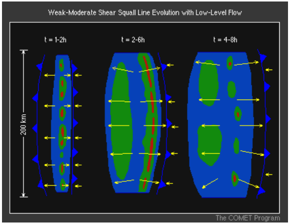
- These mesoscale pressure features are essentially in hydrostatic balance, reflecting the integrated effects of warm air and cold air in the atmospheric column above the point of observation.

Squall Lines: Weak-to-Moderate Shear, Severe Weather



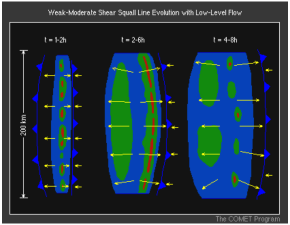
- The largest potential for localized severe weather, in the form of hail, localized downbursts, and small tornadoes, is during the early-to-mature phases, when the leading line convective cells are still quite strong.

Squall Lines: Weak-to-Moderate Shear, Severe Weather



- In moderate shear environments (especially those with high CAPE), large swaths of high winds are most likely during the mature phase, when the system has begun its transition from a vertically erect to an upshear-tilted circulation. This corresponds to the time when a rear-inflow jet is beginning to be generated, with the rear-inflow jet contributing significantly to the strength of the surface winds as it descends to the surface.

Squall Lines: Weak-to-Moderate Shear, Severe Weather



- Occasionally severe surface winds are also observed at the back edge of the stratiform precipitation region, in association with the surface wake low.

Squall Lines: Weak-to-Moderate Shear, Plane Summary

- At 1-2 hours into its evolution (early stage), the squall line is composed of independent convective cells and there is low-level convergence along the leading edge of the developing system cold pool.
- At 2-6 hours into its evolution (mature phase), the squall line has a nearly solid line of strong convective cells at the leading edge, an extensive surface cold pool, a region of enhanced stratiform precipitation separated from the leading cells by a weak echo channel, and strongly converging flow at the leading edge of the cold pool.
- At 4-8 hours into its evolution (later stage), the squall line's leading edge convection weakens, the surface cold pool surges ahead of the system, the surface flow field weakens, and the stratiform precipitation may last for hours

Squall Lines: Weak-to-Moderate Shear, Plane Summary

- The MCS life cycle may repeat itself as a new round of convection is triggered at the leading edge of the cold pool or if an external forcing feature, such as a cold front, helps to continually retrigger convection.
- The surface pressure field of a mature MCS (evolving in weak-moderate shear) is characterized by a pre-squall mesolow and a mesohigh with the surface cold pool. A wake low may be present at the back edge of the stratiform precipitation.
- In general, the weaker the shear, the faster the evolution.

Squall Lines: Weak-to-Moderate Shear, Vertical Summary

- In the early stage, cells may be upright or slightly tilted downshear, whereas the updrafts are tilted downshear. The anvil begins to spread (especially in the downshear direction).
  - The next generation of cell updrafts remain more upright than those of the initial cells.

Squall Lines: Weak-to-Moderate Shear, Vertical Summary

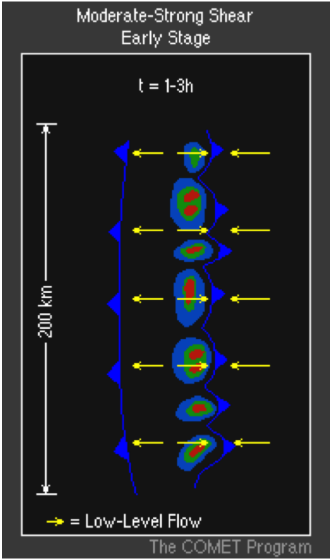
- In the mature stage, new cells continue to trigger on the leading edge of the cold pool, advect rearward, and feed into the expanding area of enhanced stratiform precipitation
  - The system updraft is now tilted upshear from the front-to-rear of the squall line (the anvil spreads upshear as well), and the rear-inflow jet develops at mid-levels, diverging when it reaches the surface.
  - A mature MCS viewed in cross section has a mesolow at mid-levels above the mesohigh with the cold pool, and a mesohigh at the top of the anvil.

Squall Lines: Weak-to-Moderate Shear, Vertical Summary

- In the late stage, the leading line convective cells become shallower and weaker and the system-scale updraft also becomes more shallow as it tilts further rearward.

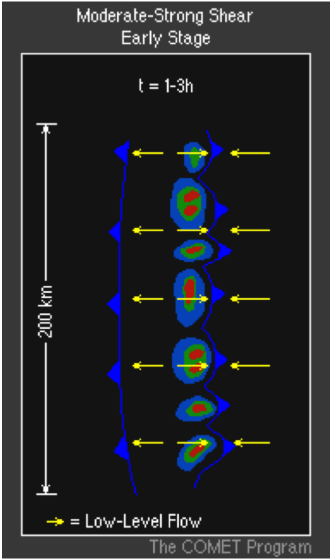
  - The rear-inflow jet continues to descend and spread out at the surface well behind the leading edge of the cold pool as the gust front considerably outruns the precipitation.
  - Localized hail, downbursts, and small tornadoes are most likely during the early-to-mature stages, but enhanced system-scale winds associated with the rear-inflow jet are most likely to occur during the mature stage.
  - MCSs evolving in large CAPE, moderate low-level shear environments are capable of producing large swaths of damaging winds, usually during their mature stage.

Squall Lines: Moderate-to-Strong Shear, Early Stage



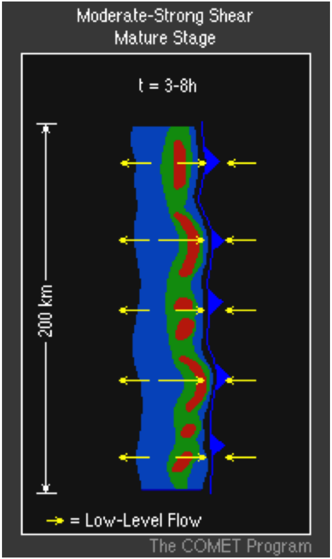
- In strongly sheared environments, the evolution of a squall line begins (t=1-3h) with an initially narrow line of strong convective cells, with light precipitation often extending downshear (east) of the convective cores.

Squall Lines: Moderate-to-Strong Shear, Early Stage



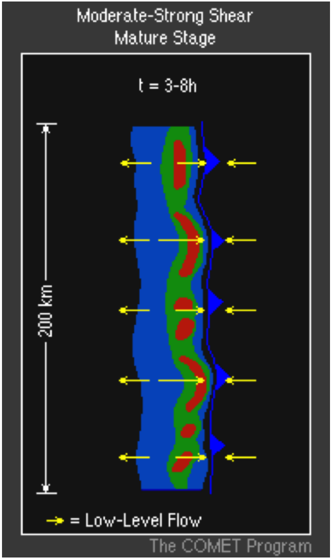
- Some of the cells may be supercellular.
- The surface flow field again depicts low-level relative inflow from the east, with divergent flow within the cold pool.

Squall Lines: Moderate-to-Strong Shear, Mature Stage



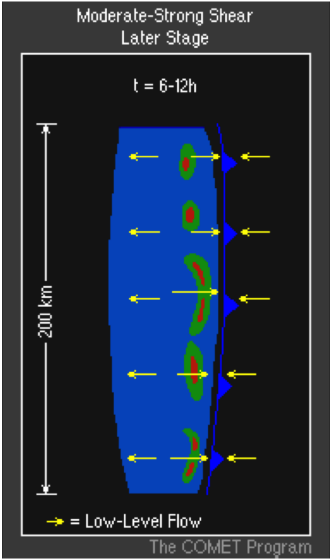
- As the system matures (t=3-8h), the relatively narrow line of strong cells persists, with bow-shaped segments of cells also beginning to develop as well.
- Lighter precipitation begins to extend somewhat rearward (upshear), but to a much less extent than in weaker shears.

Squall Lines: Moderate-to-Strong Shear, Mature Stage



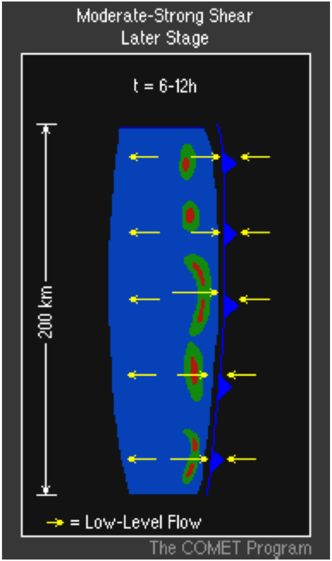
- The surface gust front maintains its location at the leading edge of the convective cells.
- The surface flow field depicts strong convergence at the surface along the leading edge of the gust front, with strong divergence within the cold pool.
- The surface pressure field depicts a strong meso-high collocated with the cold pool.

Squall Lines: Moderate-to-Strong Shear, Late Stage



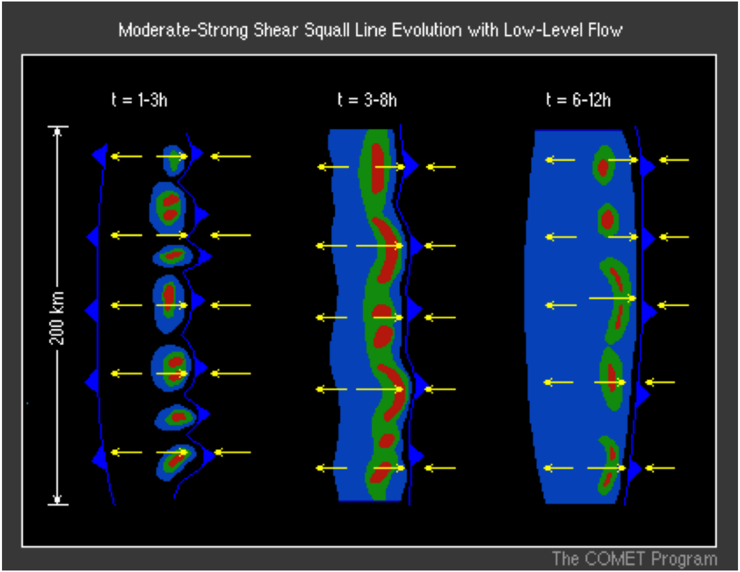
- During the later stages (t=6-12h), leading-line cells become weaker and more scattered along the line, with the region of lighter precipitation extending even further rearward (upshear).
- Just as for a weaker shear system, as the cold pool moves away from the decaying cells, a new line of cells may be triggered as the cold pool weakens or as the system encounters a more favorable environment.

Squall Lines: Moderate-to-Strong Shear, Late Stage

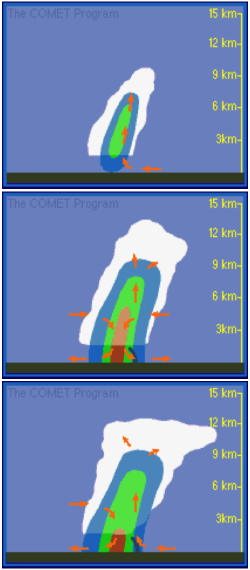


- The system may then again take on the characteristics of the mature stage and continue its evolution as before. This process has been observed to lengthen the lifetimes of convective systems considerably.
- The MCS lifecycle may repeat itself as a new round of convection is triggered at the leading edge of the cold pool, or if an external forcing feature, such as a cold front, helps to continually re-trigger convection.

Squall Lines: Moderate-to-Strong Shear, All Stages

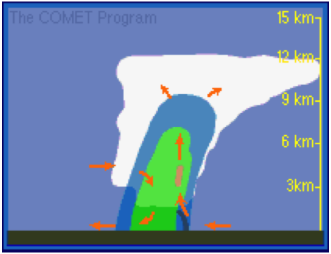


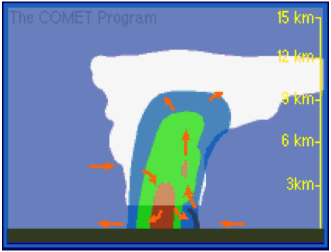
Squall Lines: Vertical Cross Section, Early Stage



- Viewed in an east-west vertical cross section, the two-dimensional evolution for strongly sheared squall lines is characterized by a much longer period of downshear-tilted structure than weakly sheared lines.
- This stage often lasts several hours before the system begins to tilt upshear (if ever).
- Individual cells may display extensive echo overhangs on their downshear side.

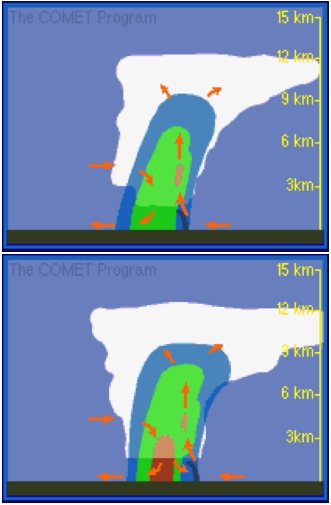
Squall Lines: Vertical Cross Section, Mature Stage





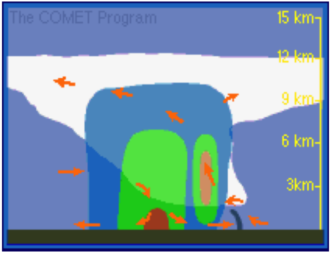
- As the system matures, new cells are continually regenerated along the downshear portion of the gust front produced by the older cells.
- In a strongly sheared system, these new updrafts still remain strong and vertically erect through mid-levels of the storm.

Squall Lines: Vertical Cross Section, Mature Stage



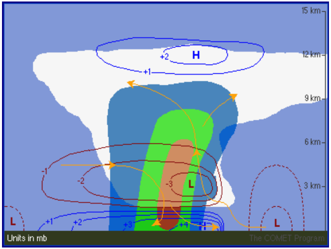
- A rear-inflow jet develops, but in this case it remains more elevated as it approaches the leading edge of the system.
- Above the rear-inflow jet, the updraft current turns abruptly rearward (upshear).
- Individual strong cells often continue to display extensive echo overhangs on their downshear side.

Squall Lines: Vertical Cross Section, Late Stage



- As the squall line decays,
  - it begins to tilt upshear
  - the leading-line convective cells weaken
  - the rear-inflow jet descends and spreads along the surface further behind the leading edge of the system.

Squall Lines: Vertical Cross Section, Pressure Field



- The pressure field of a strongly sheared squall line in its mature stage depicts a strong meso-high at the surface and a strong meso-low at mid-levels, above the surface cold pool.

Squall Lines: Moderate-to-Strong Shear, Plane Summary

- At 1-3 hours into its evolution (early stage), the squall line is a narrow line of strong convective cells (some of the cells may be supercellular) and there is strong low-level convergence along the leading edge of the developing system cold pool.
- At 3-8 hours into its evolution (mature phase), bow-shaped segments may begin to develop. Compared to a weakly sheared system, the stratiform precipitation region is narrower and there is usually no area of enhanced stratiform precipitation.

Squall Lines: Moderate-to-Strong Shear, Plane Summary

- The surface flow field is strongly convergent at the leading edge of the cold pool, which remains close to the leading edge of the precipitation.
- At 6-12 hours into its evolution (later stage), the squall line's leading edge convection begins to weaken, the surface cold pool begins to move ahead of the system, and lighter precipitation begins to fall over a broader area behind the system.

Squall Lines: Moderate-to-Strong Shear, Plane Summary

- The MCS lifecycle may repeat itself as a new round of convection is triggered at the leading edge of the cold pool or if an external forcing feature, such as a cold front, helps to continually re-trigger convection.
- The surface pressure field of a mature MCS (evolving in moderate-strong shear) is characterized by a pre-squall meso-low and a strong meso-high with the surface cold pool. A weak wake low is also possible.
- In general, the stronger the shear, the longer this evolution takes. A strongly sheared system may live for ¿ 12 hours, as long as conditions continue to be favorable.

Squall Lines: Moderate-to-Strong Shear, Vertical Summary

- In the early stage, the system has a much longer period of downshear-tilted structure than weakly sheared systems, and individual cells may display extensive echo overhangs on their downshear side.
- In the mature stage, the updrafts within the new cells being triggered in the downshear direction by the cold pool remain strong and vertically erect through the mid-levels of the storm.

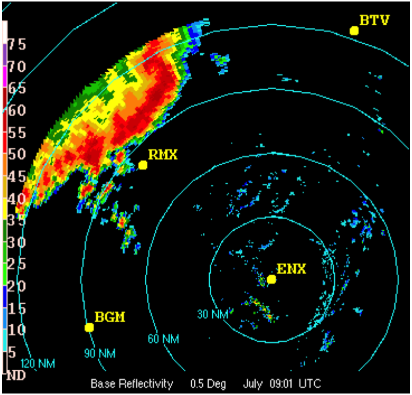
Squall Lines: Moderate-to-Strong Shear, Vertical Summary

- When the rear-inflow jet develops, it remains more elevated than in weakly sheared systems as it approaches the leading edge of the system. It descends to the surface and creates potentially severe winds.
- A mature MCS in a stronger shear environment has a strong meso-low at mid-levels above the meso-high with the cold pool and a meso-high at the top of the anvil.

Squall Lines: Moderate-to-Strong Shear, Vertical Summary

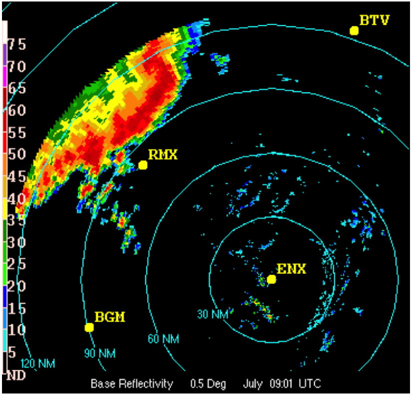
- In the later stage, the system may finally began to tilt upshear, and the leading line convection begins to weaken.
- The rear-inflow jet continues descending to the surface behind the leading edge of the cold pool, and the gust front begins to outrun the precipitation.
- Hail, strong winds, and tornadoes are possible with any strong cell in the line during the early and mature stages (especially with any supercell), but enhanced system-scale winds associated with the rear-inflow jet and bowing line segments are most likely during the mature stage.

Squall Lines: 3D Evolution



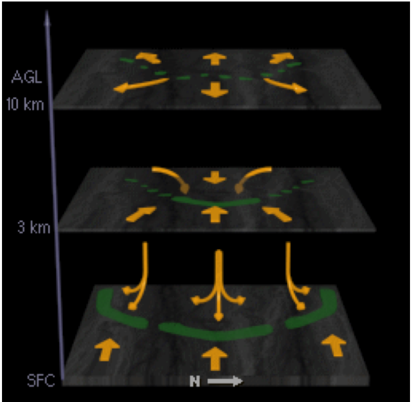
- The two-dimensional evolution described for the early-to-mature phases of a squall line generally applies to the middle portion of most squall lines.

Squall Lines: 3D Evolution



- However, significant three-dimensional mesoscale flow features can evolve at the ends of a squall line or at breaks within the line, which can significantly alter the subsequent evolution of the system.
- The most prominent of these features is a set of mid-level mesoscale vortices, referred to as "line-end" or "bookend" vortices.

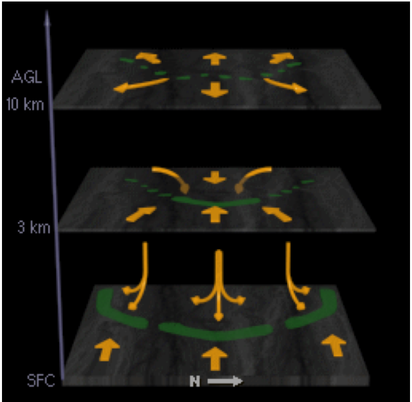
Squall Lines: 3D Evolution



Conceptual model of mature line without Coriolis forcing.
Modified from Skamarock, Weisman, and Klemp, 1994

- Viewing all levels of the storm, the structure of the system during its symmetric phase (early in the evolution) is characterized by low-level divergent flow with the cold pool, symmetric line-end vortices at mid-levels, and the rear-inflow jet concentrated between the vortices.

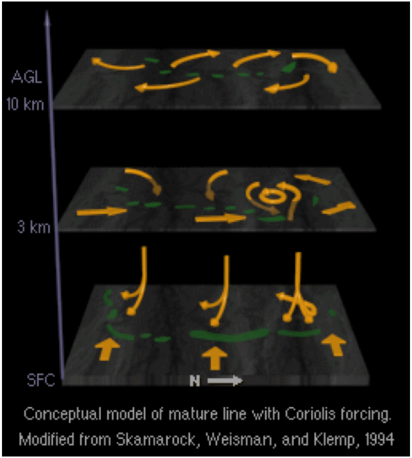
Squall Lines: 3D Evolution



Conceptual model of mature line without Coriolis forcing.
Modified from Skamarock, Weisman, and Klemp, 1994

- Aloft, we find divergent flow, with weaker vortices of opposite rotational sense above the mid-level vortices at the northern and southern ends of the system.

Squall Lines: 3D Evolution



- During the asymmetric phase (later in the evolution), a dominant cyclonic vortex is evident at mid-levels, while both the low-level and upper-level divergent outflows turn anticyclonically.

Squall Lines: Development of Supercell Lines

- Most often, squall lines are composed of ordinary cells.
- But occasionally, when the environment exhibits strong vertical wind shear at both lower (0-3 km AGL) and upper levels (3-6 km AGL), a squall line may also be composed of supercells.
- During the early stages of such systems, supercells often may be spread along the entire extent of the line.

Squall Lines: Development of Supercell Lines

- However, the circulations of these supercells are often quickly disrupted as cells interact with each other along the line.
- Due to cell interactions, certain locations within a line may be favored for supercell development and maintenance, depending on the shape and orientation of the environmental shear profile relative to the orientation of the squall line.
- In any scenario, new convective cells may also be triggered along the spreading cold pool between the supercells, making cell interactions even more complicated.

Squall Lines: Development of Supercell Lines

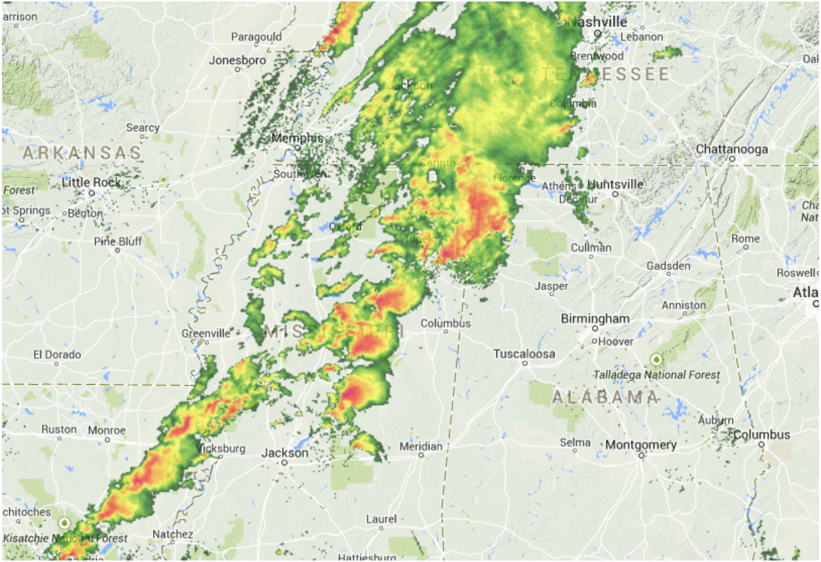


Figure: April 28, 2014 at 2044 UTC

The End