

Convective Dynamics

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Squall Lines

- 3D Evolution

- Development of Supercell Lines

- Dynamics

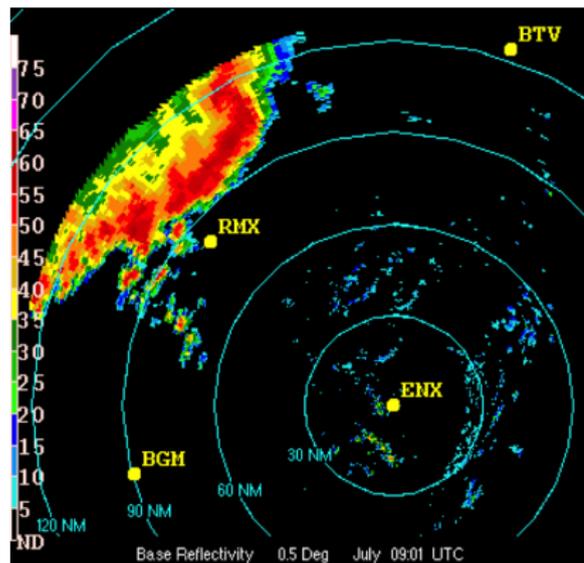
- RKW Theory

- Early 2D Evolution

- Rear-Inflow Jet

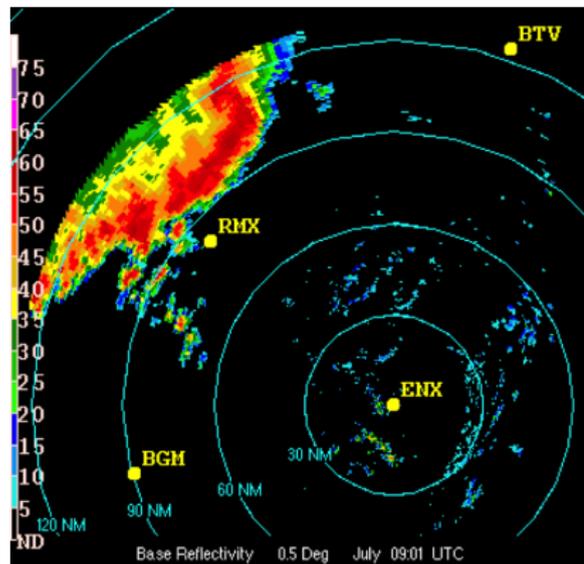
- Model Simulations

Squall Lines: 3D Evolution



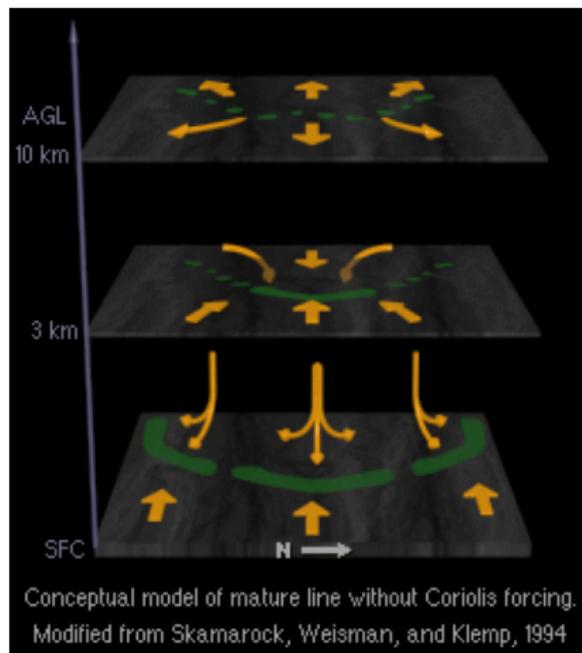
- ▶ The two-dimensional evolution described for the early-to-mature phases of a squall line generally applies to the middle portion of most squall lines.

Squall Lines: 3D Evolution



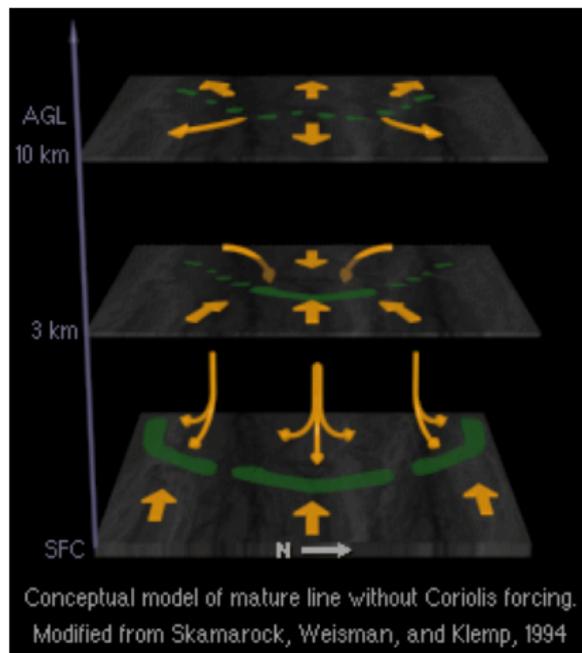
- ▶ However, significant three-dimensional mesoscale flow features can evolve at the ends of a squall line or at breaks within the line, which can significantly alter the subsequent evolution of the system.
- ▶ The most prominent of these features is a set of mid-level mesoscale vortices, referred to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

Squall Lines: 3D Evolution



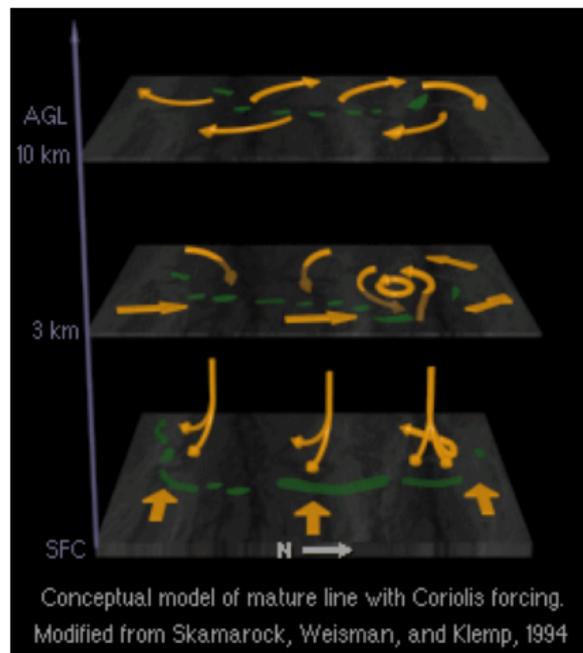
- ▶ Viewing all levels of the storm, the structure of the system during its symmetric phase (early in the evolution) is characterized by low-level divergent flow with the cold pool, symmetric line-end vortices at mid-levels, and the rear-inflow jet concentrated between the vortices.

Squall Lines: 3D Evolution



- ▶ 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

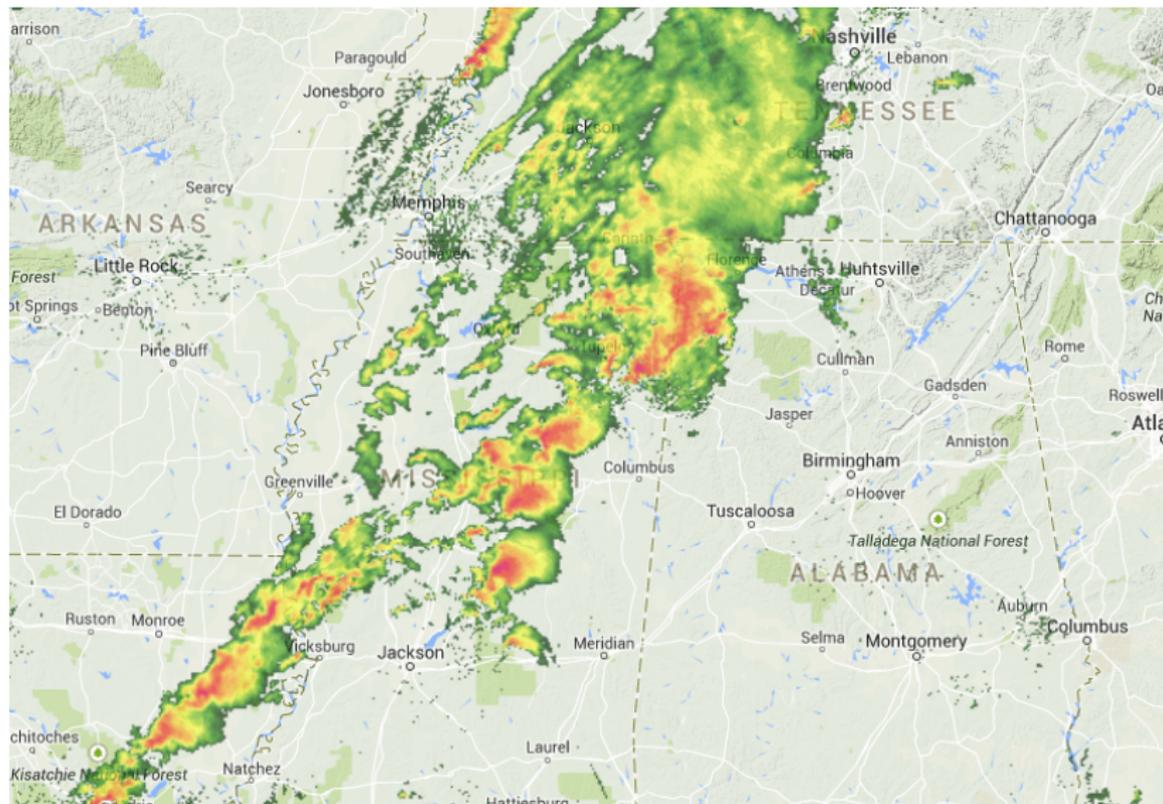


Figure: April 28, 2014 at 2044 UTC

Squall Lines: Physical Processes Responsible for Dynamics

We have described the observed features and evolution of squall lines. Questions remain, as to:

- ▶ Why does the strength and longevity of a squall line depend on the strength of environmental vertical wind shear?
- ▶ What produces the mesoscale pressure patterns observed with squall lines?
- ▶ How is a rear-inflow jet generated, what controls its strength, and what impact does it have on squall line strength and evolution?
- ▶ How does the Coriolis force impact squall line evolution?
- ▶ How can we better anticipate whether an squall line is apt to produce severe weather?

Squall Lines: Equations to be Used

- ▶ The fundamental equations for understanding convective motions are the horizontal and vertical momentum equations.
- ▶ The horizontal momentum equations relate horizontal accelerations to horizontal pressure gradients and Coriolis forcing, while the vertical momentum equation relates vertical accelerations to buoyancy forces and vertical pressure gradient forces.
- ▶ Also useful are the vorticity equations that can be derived from the momentum equations. One example is the y -component of vorticity equation we presented earlier when discussing gust front circulations.

Squall Lines: RKW Theory on Cold Pool



When discussing the multicell storms, we discussed how the interaction between the system-generated cold pool and the ambient low-level shear strongly modulates the tendency to generate new cells in multiple cell systems. In a homogeneous environment, the strongest, most long-lived multiple cell systems occur in environments characterized by strong, low-level vertical wind shear.

Squall Lines: RKW Theory on Cold Pool



Rotunno, Klemp, and Weisman, (1988) proposed that the optimal condition for the generation of new convective cells is when there is a balance between the horizontal vorticity produced by the cold pool and the opposite horizontal vorticity associated with the ambient low-level vertical wind shear on the downshear flank of the system

Squall Lines: RKW Theory on Cold Pool



Knowledge of the processes underlying cold pool/shear interactions is also critical for understanding the strength, longevity, and evolutionary character of long-lived squall lines.

Squall Lines: RKW Theory on Cold Pool

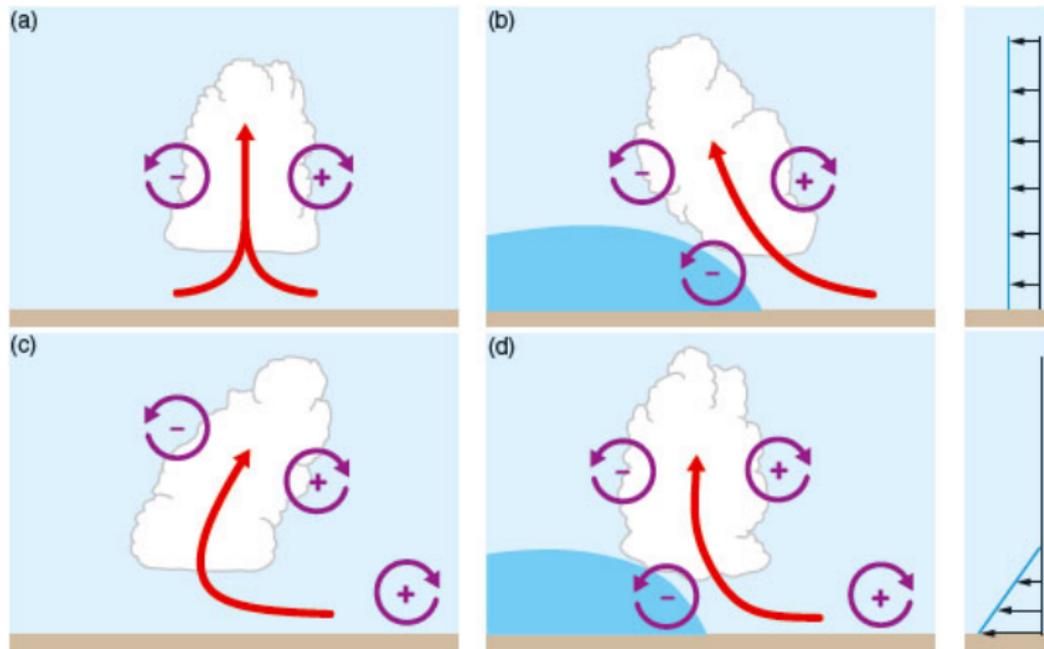
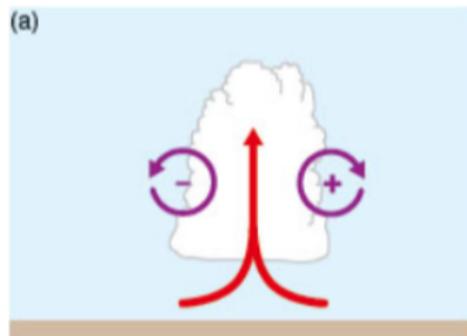


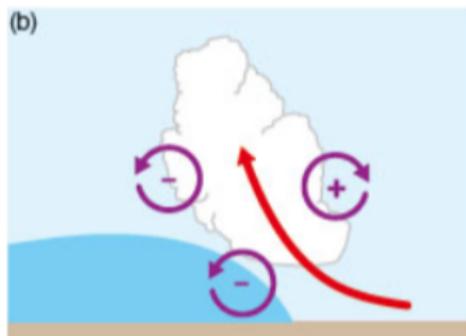
Figure: Schematic diagram showing how a buoyant updraft may be influenced by environmental wind shear and/or a cold pool.

Squall Lines: RKW Theory on Cold Pool



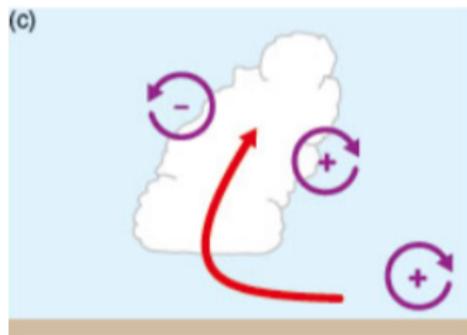
(a) - With no environmental shear and no cold pool, the axis of the updraft produced by the thermally created, symmetric vorticity distribution is vertical.

Squall Lines: RKW Theory on Cold Pool



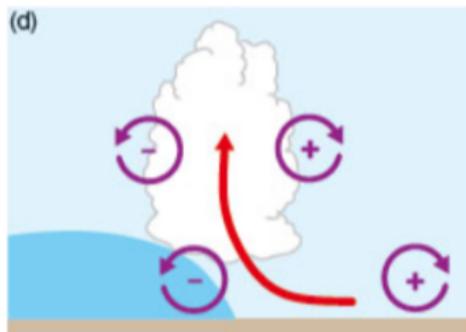
(b) - With a cold pool, the distribution is biased by the negative vorticity of the underlying cold pool, causing the updraft to tilt over the cold pool.

Squall Lines: RKW Theory on Cold Pool



(c) - With environmental shear and no cold pool, the distribution is biased toward positive vorticity, causing the updraft to lean downshear.

Squall Lines: RKW Theory on Cold Pool



(d) - With both a cold pool and shear, the two effects may negate each other and promote an erect updraft.

Squall Lines: RKW Theory on Cold Pool

RKW looked for a quantitative criterion for the low-level shear needed to balance a cold pool.

RKW also set out to distinguish the physical difference between a cold pool spreading into a no-shear environment from that in an environment with low-level shear.

Squall Lines: RKW Theory on Cold Pool

Recall that the equation governing vorticity in the y -direction is

$$\frac{d\eta}{dt} = -\frac{\partial B}{\partial x},$$

which may be expanded as

$$\frac{\partial \eta}{\partial t} = -\frac{\partial(u\eta)}{\partial x} - \frac{\partial(w\eta)}{\partial z} - \frac{\partial B}{\partial x},$$

where

$$\eta = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}$$

is vorticity and B is the total buoyancy.

Squall Lines: RKW Theory on Cold Pool

Next, we fix ourselves in a reference frame moving with the edge of the cold air. We then integrate the previous equation from a point to the left, $x = L$, to a point to the right, $x = R$, of the cold-air edge, and from the ground to some level, $z = d$.

$$\underbrace{\frac{\partial}{\partial t} \int_L^R \int_0^d \eta dz dx}_{\text{tendency}} = \underbrace{\int_0^d (u\eta)_L dz}_{\text{flux at left}} - \underbrace{\int_0^d (u\eta)_R dz}_{\text{flux at right}} \\ - \underbrace{\int_L^R (w\eta)_d dx}_{\text{flux at top}} - \underbrace{\int_0^d (B_L - B_R) dz}_{\text{net generation}}$$

Squall Lines: RKW Theory on Cold Pool

Assumptions

- ▶ a steady balance, so $\partial/\partial t = 0$
- ▶ negligible buoyancy of air approaching cold pool, so $B_R = 0$
- ▶ far away from the edge of the cold air, $\eta \approx \partial u/\partial z$

Squall Lines: RKW Theory on Cold Pool

Applying assumptions yields

$$0 = \left(\frac{u_{L,d}^2}{2} - \frac{u_{L,0}^2}{2} \right) - \left(\frac{u_{R,d}^2}{2} - \frac{u_{R,0}^2}{2} \right) - \int_L^R (w\eta)_d dx + \int_0^d B_L dz$$

Squall Lines: RKW Theory on Cold Pool

Next, we consider a situation where the cold air is stagnant (relative to the cold-air edge), so that $u_{L,0} = 0$, and restricted to a height, $z = H$, where $H < d$. Applying these assumptions leads to

$$0 = \frac{u_{L,d}^2}{2} - \left(\frac{u_{R,d}^2}{2} - \frac{u_{R,0}^2}{2} \right) - \int_L^R (w\eta)_d dx + \int_0^H B_L dz$$

Squall Lines: RKW Theory on Cold Pool

Consider a situation with low-level shear (panel d earlier).

RKW looked for the optimal state where the low-level flow is turned by the cold pool in such a way as to exit as a vertically oriented jet.

Thus, we set $u_{L,d}$, $u_{R,d}$, and $\int_L^R (w\eta)_d dx = 0$.

Squall Lines: RKW Theory on Cold Pool

The result is then

$$\Delta u = c,$$

where

$$\Delta u = u_{R,d} - u_{R,0} = -u_{R,0}$$

and

$$c^2 = 2 \int_0^H (-B_L) dz = 2g \frac{-\Delta\theta}{\theta_0} H = 2g \frac{\Delta\rho}{\rho_0} H$$

$$\rightarrow c = \sqrt{2gH \frac{\Delta\rho}{\rho_0}}$$

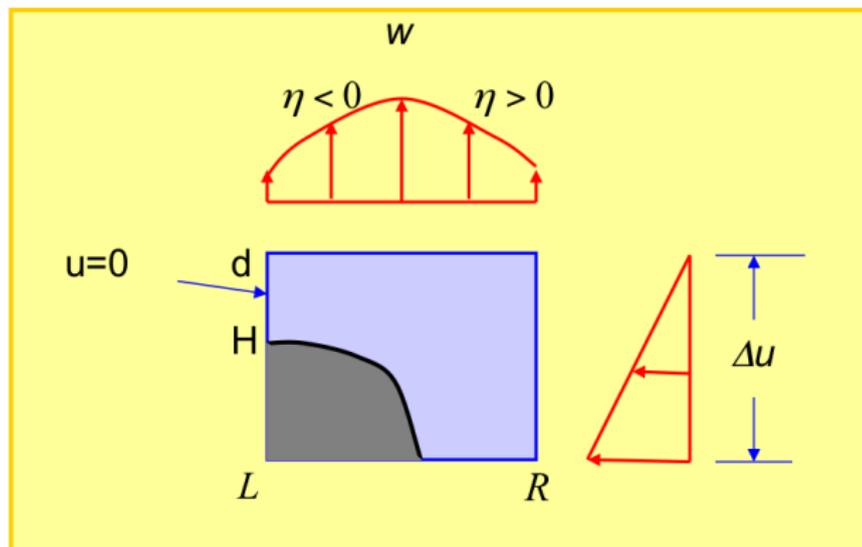
which is exactly the density current propagation speed we derived earlier!

Squall Lines: RKW Theory on Cold Pool

Therefore the optimal condition obtained based on RKW's vorticity budget analysis says that the shear magnitude in the low-level inflow should be equal to the cold pool propagation speed.

Physically, this means that the import of the positive vorticity associated with the low-level shear just balances the net buoyancy generation of negative vorticity by the cold pool in the volume.

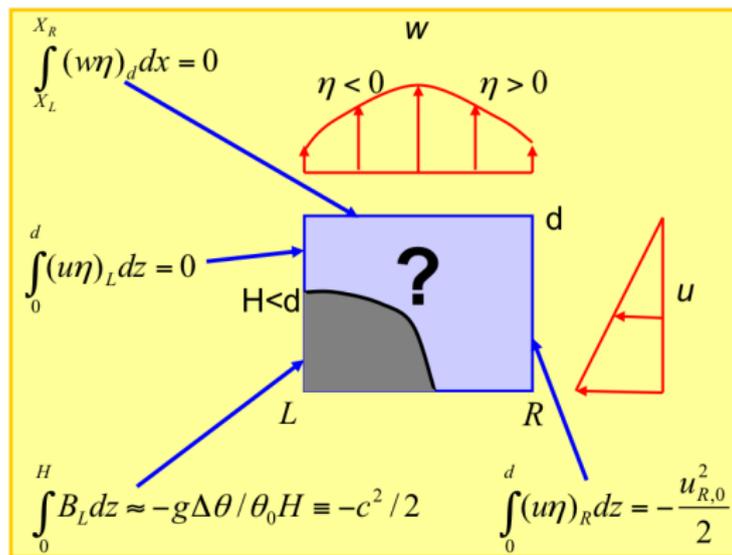
Squall Lines: RKW Theory on Cold Pool



$$\Delta u = -u_{R,0} = c$$

$$\frac{\partial(u\eta)}{\partial x} + \frac{\partial(w\eta)}{\partial z} = -\frac{\partial B}{\partial x}$$

Squall Lines: RKW Theory on Cold Pool



$$\frac{\partial(u\eta)}{\partial x} + \frac{\partial(w\eta)}{\partial z} = -\frac{\partial B}{\partial x}$$

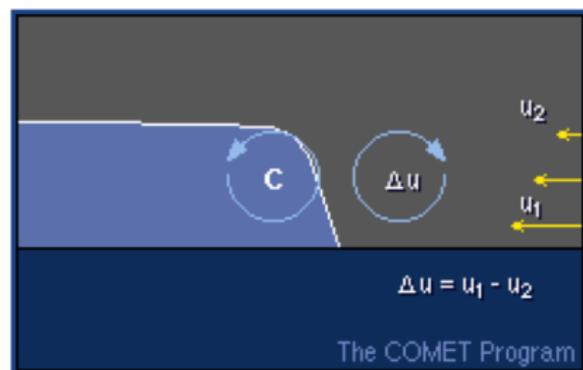
$$0 \qquad \qquad \qquad 0$$

$$\int_0^d (u\eta)_R dz - \int_0^d (u\eta)_L dz + \int_L^R (w\eta)_d dx$$

$$- \int_L^R (w\eta)_0 dx = \int_0^H (B_L - B_R) dz$$

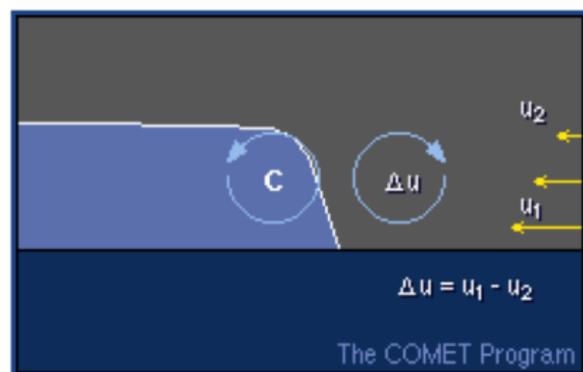
$$\Delta u = -u_{R,0} = c$$

Squall Lines: RKW Theory on Cold Pool



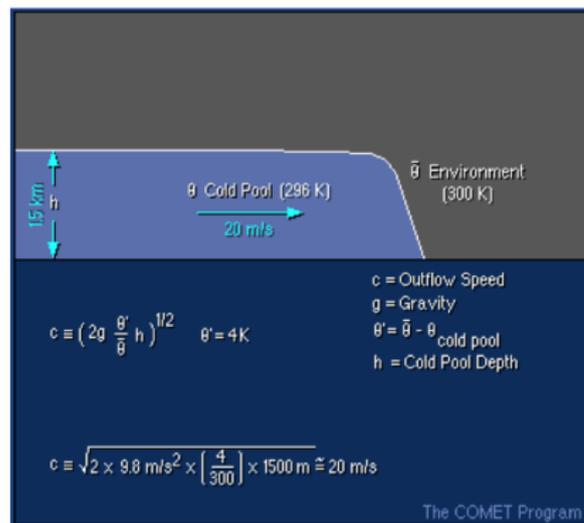
- ▶ The relative balance between the cold pool generated horizontal vorticity and the ambient shear can be quantified via the ratio $c/\Delta u$.

Squall Lines: RKW Theory on Cold Pool



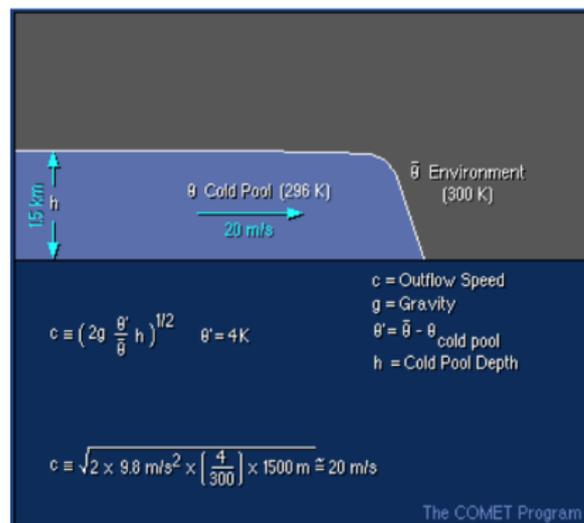
- ▶ In this ratio, c represents the strength of the cold pool circulation, given by the theoretical speed of propagation.
- ▶ Δu represents the strength of the circulation associated with the ambient shear, given by the magnitude difference between the component of ambient wind perpendicular to the cold pool at the surface, U_1 , and at 2.5 km AGL, U_2 .

Squall Lines: RKW Theory on Cold Pool



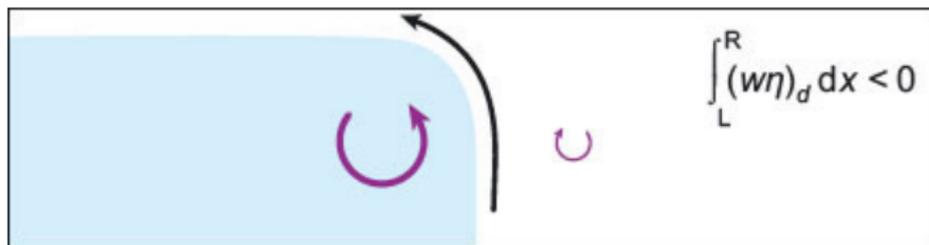
- ▶ As an example, if $\Delta\theta = -4$ within a 1.5 km deep cold pool ($h = 1.5$), c would be about 20 ms^{-1} .

Squall Lines: RKW Theory on Cold Pool

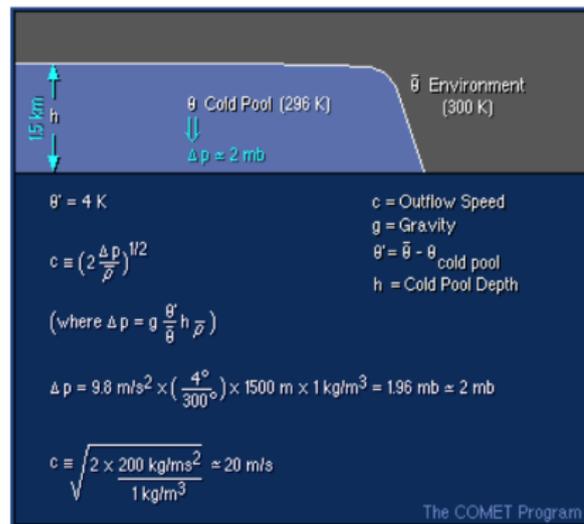


- ▶ $c/\Delta u = 1$ represents the optimal state for deep lifting by the cold pool, with values less than 1 signifying that the ambient shear is too strong relative to the cold pool. Values greater than 1 signify that the cold pool is too strong for the ambient shear.
- ▶ $c/\Delta u$ can also be used to understand the two-dimensional evolution of a squall line, providing clues to help us anticipate its strength and longevity.

Squall Lines: RKW Theory on Cold Pool

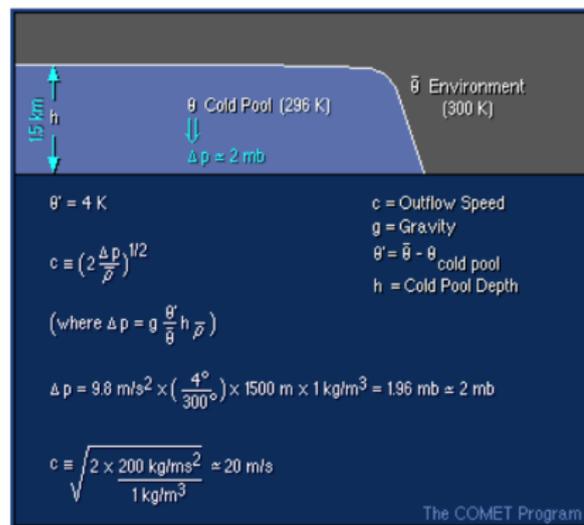


Squall Lines: RKW Theory on Cold Pool



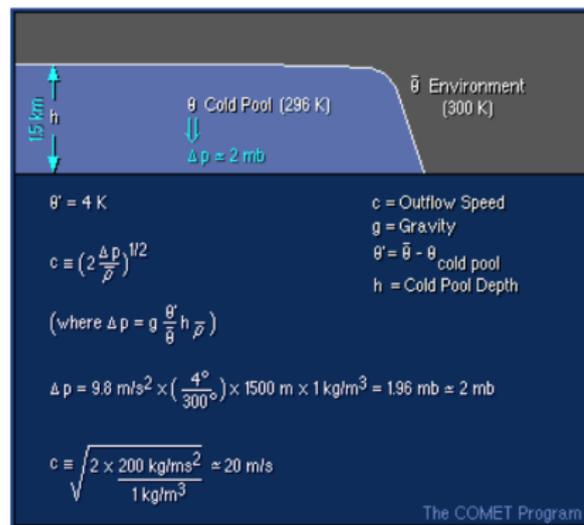
- ▶ Since potential temperature perturbations within the cold pool can be directly related to the hydrostatic pressure change within the cold pool, the speed of the cold pool (c) can be calculated by measuring the change of pressure as the cold pool passed overhead, instead of measuring the change of temperature.

Squall Lines: RKW Theory on Cold Pool



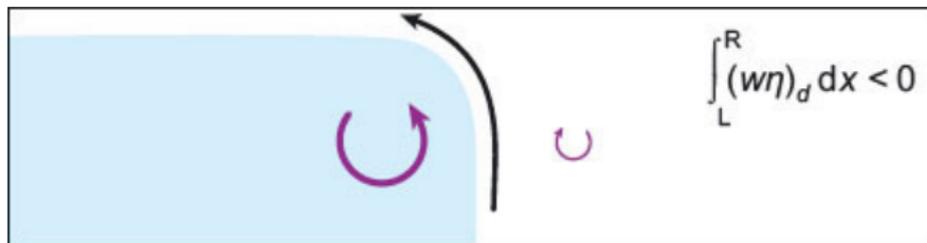
- ▶ This method has an advantage over using the temperature perturbation method since the pressure change at the surface represents the integrated affects over the depth of the cold pool. Thus, one does not have to know the depth of the cold pool (h) to make the calculation.

Squall Lines: RKW Theory on Cold Pool



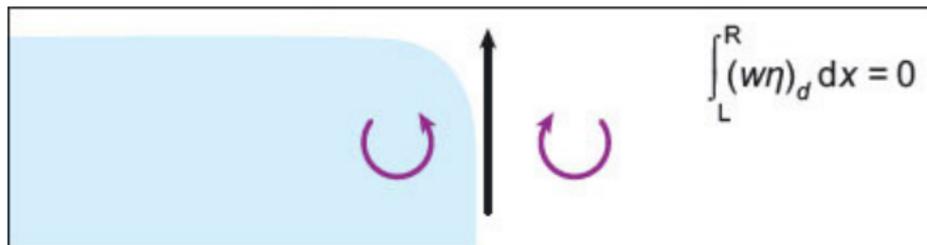
- ▶ Again using our example of a cold pool with a 4 K potential temperature deficit over 1.5 km, we can see that it translates to a pressure excess of $\sim 2 \text{ mb}$. When we calculate the speed of the cold pool, c , for an observed pressure change of $\sim 2 \text{ mb}$, we again get 20 ms^{-1} .

Squall Lines: RKW Theory on Cold Pool



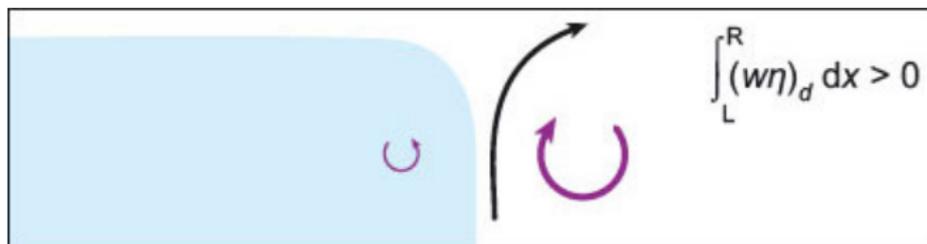
Consider the simple case of a two-dimensional cold pool spreading in an environment with little or no vertical wind shear. From the perspective of horizontal vorticity, a cold pool in the absence of strong ambient vertical wind shear tends to drag air up, over, and behind the leading edge of cold air.

Squall Lines: RKW Theory on Cold Pool



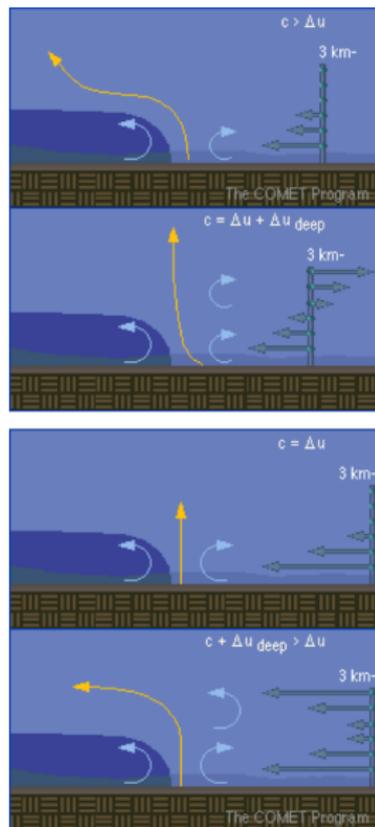
If there is an optimal amount of ambient, low-level vertical wind shear, such that the horizontal vorticity associated with it balances the opposite horizontal vorticity produced on the downshear side of the spreading cold pool, a more vertically oriented and deeper updraft will be produced due to the interacting vorticities.

Squall Lines: RKW Theory on Cold Pool



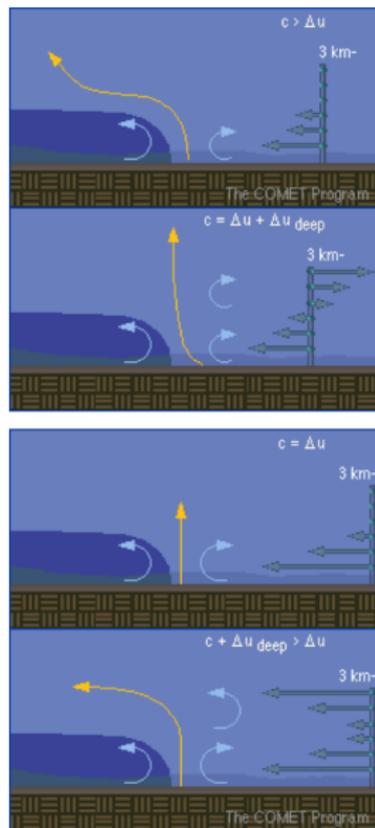
If the horizontal vorticity associated with the ambient vertical wind shear is stronger than that produced by the cold pool, then air parcels lifted at the leading edge of the cold pool will be tilted downshear. They will not be lifted as much as when a vorticity balance is in place.

Squall Lines: RKW Theory on Cold Pool



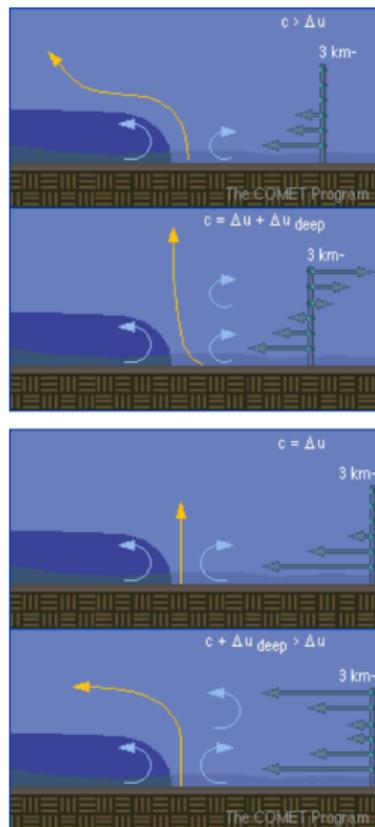
- ▶ The shear layer that is most important for determining the depth and strength of lifting at the leading edge of the cold pool is the one coinciding with the depth of the cold pool, usually from the surface to about 1.5-2 km AGL.

Squall Lines: RKW Theory on Cold Pool



- ▶ However, shear over a deeper layer above the cold pool also contributes to some degree. For instance, deeper shear may help to maintain deeper, more upright lifting in a case where $c/\Delta u > 1$. For this reason, we use 0-3 km AGL to define the effective shear layer.

Squall Lines: RKW Theory on Cold Pool



- ▶ Similarly, if the shear reverses above the cold pool, as in a jet-type wind profile, the updraft current aloft may tilt back over the cold pool, despite a favorable $c/\Delta u$ balance at lower levels.

Squall Lines: Cold Pool/Shear Interactions Summary

- ▶ The system-generated cold pool and the ambient low-level shear strongly modulate the tendency to generate new cells in multiple cell systems, including multicell squall lines.
- ▶ The deepest updrafts occur when the horizontal vorticity generated along the cold pool's leading edge is nearly equal in magnitude to, and has rotation of opposite sense to the horizontal vorticity associated with the low-level vertical wind shear.
- ▶ When the low-level wind shear is weak and is associated with weaker horizontal vorticity than the cold pool, the updraft at the leading edge of the cold pool is tilted upshear and is not as deep and strong as when they are in balance.

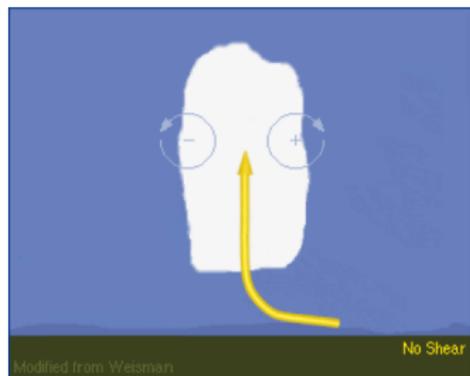
Squall Lines: Cold Pool/Shear Interactions Summary

- ▶ When the low-level wind shear is stronger and is associated with stronger horizontal vorticity than the cold pool, the updraft at the leading edge of the cold pool is tilted downshear and is not as deep and strong as when they are in balance.
- ▶ This cold pool/low-level shear relationship can be quantified as a ratio of the speed of the cold pool, c , over the value of the line-normal low-level vertical wind shear, Δu .

Squall Lines: Cold Pool/Shear Interactions Summary

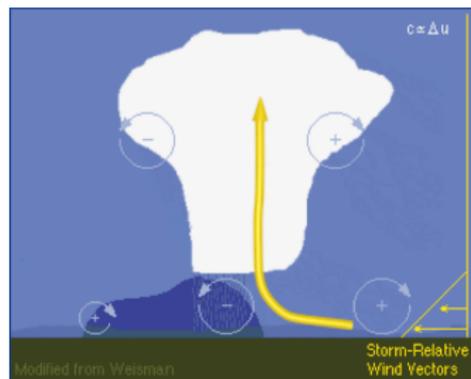
- ▶ $c/\Delta u = 1$ represents the optimal state for deep lifting by the cold pool.
- ▶ $c/\Delta u < 1$ signifies that the ambient shear is too strong relative to the cold pool.
- ▶ $c/\Delta u > 1$ signifies that the cold pool is too strong for the ambient shear.
- ▶ This balance is significant for anticipating the strength and longevity of an squall line

Early 2D Evolution - Phase 1: Initiation



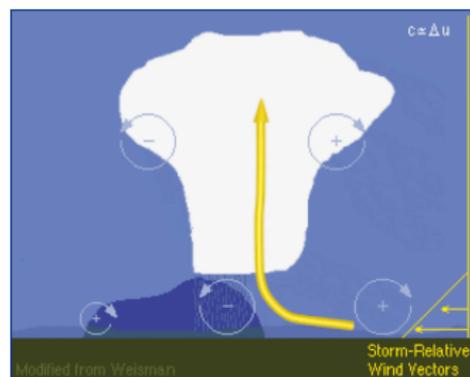
- ▶ Initially, a series of convective cells develops along some pre-existing linear forcing feature.
- ▶ Since these convective cells are buoyant, horizontal vorticity is generated equally on all sides of the cells.
- ▶ In the absence of vertical wind shear, this would produce an upright circulation.
- ▶ However, since there is vertical wind shear, the additive influence of the horizontal vorticity associated with the shear on the downshear side of the cells causes them to lean downshear.

Early 2D Evolution - Phase 2: Strong Cells



- ▶ Once the system begins to produce rainfall and a cold pool forms, the cold pool circulation is often initially weak relative to the ambient shear, with subsequent cells continuing to lean predominately downshear, like the initial cell.
- ▶ However, over time, the sequence of new cells continues to strengthen the cold pool, and unless the ambient shear is exceptionally strong, the cold pool circulation eventually becomes strong enough to balance the horizontal vorticity associated with the ambient shear.

Early 2D Evolution - Phase 2: Strong Cells



- ▶ With this balance ($c/\Delta u = 1$) in place, the strongest and deepest lifting is produced along the leading edge of the cold pool. Often, it is during this stage that the most intense and erect convective cells are observed along the squall line, with new cells regularly being triggered as old cells decay.
- ▶ Because the cells characteristically move at the same speed as the gust front in this stage, the convective line remains relatively narrow.

Early 2D Evolution - Phase 3: Tilting Upshear



- ▶ As the cold pool continues to strengthen, the cold pool circulation often eventually overwhelms the ambient vertical wind shear vorticity ($c/\Delta u > 1$). Cells begin to tilt upshear and advect rearward over the cold pool (relative to the gust front).

Early 2D Evolution - Phase 3: Tilting Upshear



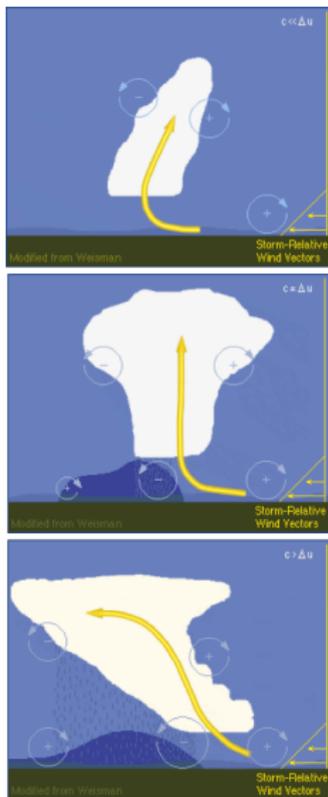
- ▶ During this stage, the squall line takes on the appearance of a classic multiple cell system, with a sequence of cells that initiate at the leading edge, then mature and decay as they advect rearward over the cold pool. The leading-line convective cells usually become less intense during this phase because the lifting at the leading edge is not as strong or deep as it is during the stage of optimal balance.

Early 2D Evolution - Phase 3: Tilting Upshear



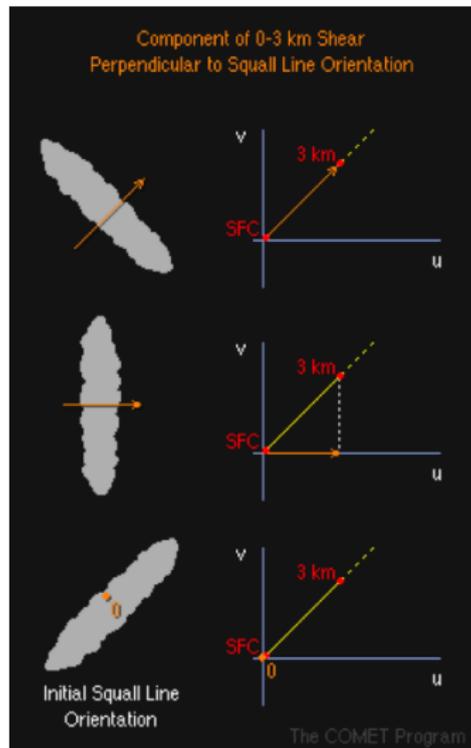
- ▶ The rearward advecting cells produce an expanding region of lighter precipitation extending behind the strong, leading-line convection. This rearward expansion of the rainfield creates the trailing stratiform precipitation region associated with mature MCSs. It is in this phase that the system begins to take on a mesoscale flow structure, including the development of a mid-level mesolow and rear-inflow jet.

Early 2D Evolution - Evolution Timeframe



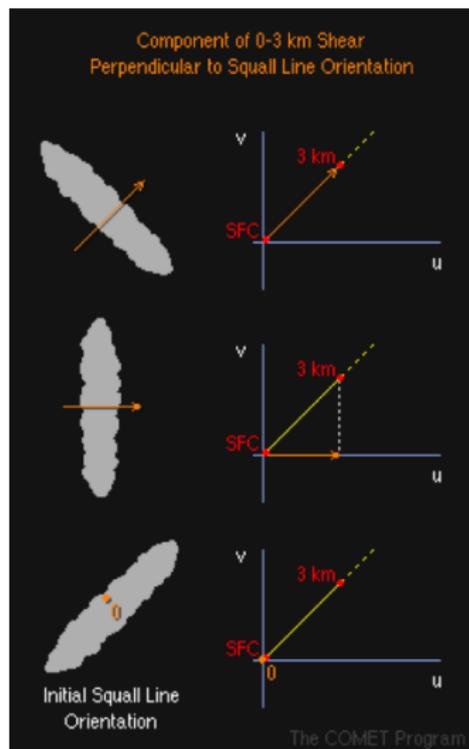
- ▶ The period over which this evolution takes place depends on both the strength of the cold pool as well as the magnitude of the low-level vertical wind shear, and can vary from 2-3 hours to over 8 hours in some cases.
- ▶ In general, for midlatitude conditions (which produce fairly strong cold pools) a $\Delta u \leq 10 \text{ ms}^{-1}$ produces this evolution over a 2-6 hour period, while $\Delta u \geq 20 \text{ ms}^{-1}$ slows the evolution to between 4-8 hours.

Early 2D Evolution - Shear Orientation



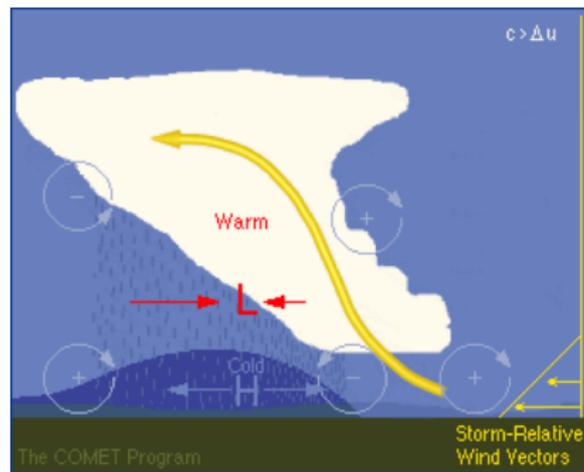
- ▶ It's important to remember that for a squall line the only component of low-level shear that contributes to the $c/\Delta u$ balance is the component perpendicular to squall line orientation.

Early 2D Evolution - Shear Orientation



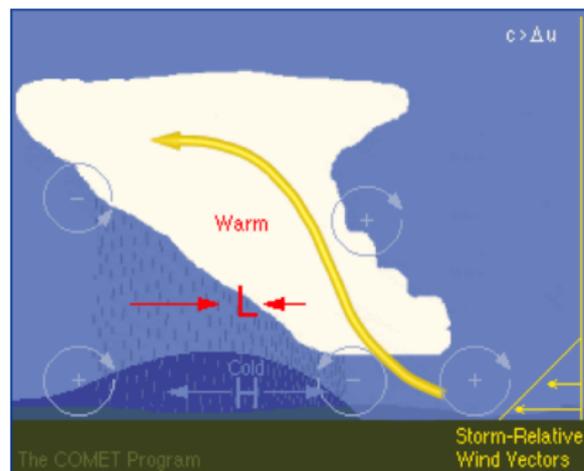
- ▶ If we had southwesterly shear, a squall line oriented from northwest to southeast (top) would feel the full effects of the shear, while a squall line oriented northeast-southwest (bottom) would evolve as if there were no low-level shear at all. However, the cells at the ends of the squall line do not necessarily follow this rule because they can interact with the shear more like isolated cells.

Rear-Inflow Jet: Pressure Field



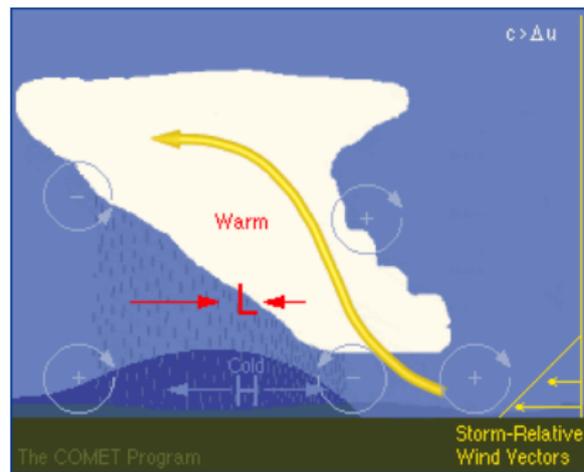
- ▶ As the squall line continues to evolve in its mature stage, the spreading of the convective cells rearward transports warm air aloft as well. In addition, the deeper portion of the surface cold pool also extends rearward, in response to the rearward expanding rainfield.

Rear-Inflow Jet: Pressure Field



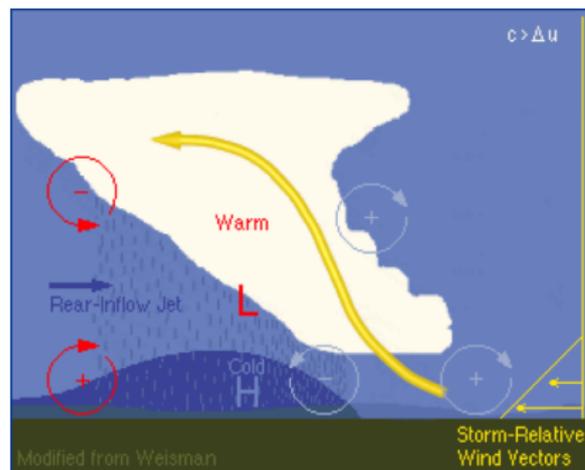
- ▶ A pool of warm air aloft over a cold pool at the surface produces lower pressure at mid levels and higher pressure at the surface. The flow field responds by diverging at the surface and converging at mid levels.

Rear-Inflow Jet: Pressure Field



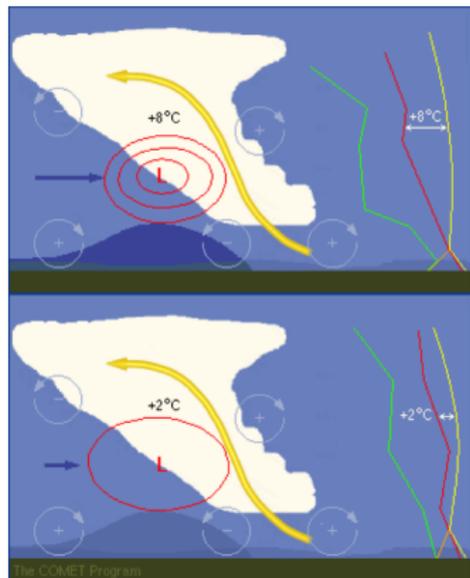
- ▶ The flow that converges in from the rear of the system at mid levels is known as the rear-inflow jet (RIJ). The convergence from the front of the system tends to be blocked by the updraft, so most of the flow converges in from the rear of the system.

Rear-Inflow Jet: Horizontal Vorticity



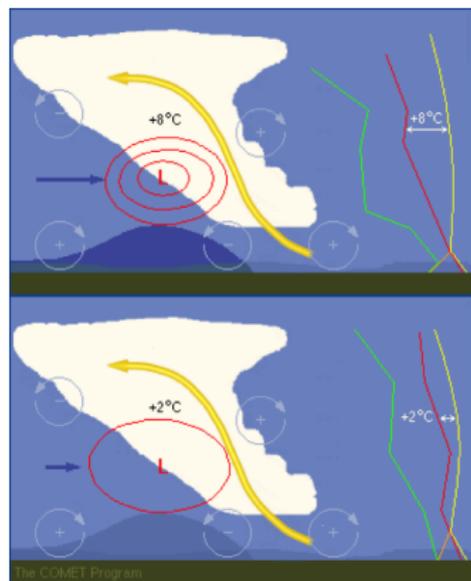
- ▶ From the horizontal vorticity perspective, the horizontal buoyancy gradients associated with the back edge of the warm air aloft and back edge of the cold pool at the surface generate a vertically stacked horizontal vorticity couplet. This couplet is responsible for the generation of the rear-inflow jet.

Rear-Inflow Jet: Strength



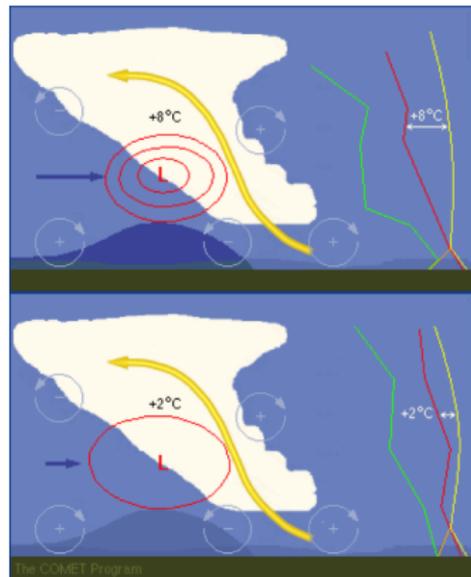
- ▶ Since the rear-inflow jet is generated in response to the horizontal buoyancy gradients at the back edge of the system, the strength of the rear-inflow jet is directly related to the strength of those buoyancy gradients, both aloft and within the cold pool. The strength of these buoyancy gradients is directly related to the relative warmth of the air within the front-to-rear (FTR) ascending current, as well as the relative coolness of the surface cold pool.

Rear-Inflow Jet: Strength



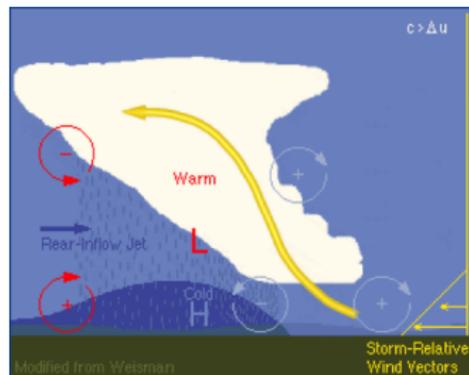
- ▶ The potential temperature excess within the FTR ascending current is directly related to the thermodynamic instability of the air mass.
- ▶ If the maximum temperature excess for a surface parcel rising through the atmosphere is only 2°C , then one could expect a maximum of 2°C of warming within the FTR current.
- ▶ Likewise, if the maximum temperature excess for the rising surface parcel was 8°C , then one could expect up to 8°C of warming within the FTR current.

Rear-Inflow Jet: Strength



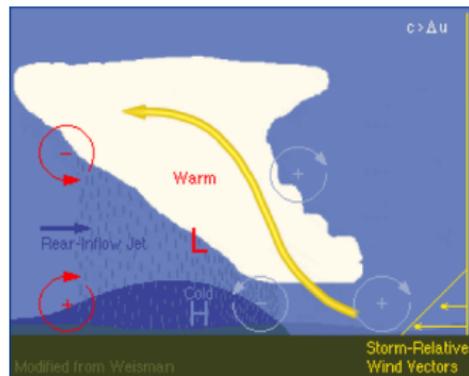
- ▶ The strength of the cold pool is also directly related to the thermodynamic instability in the environment. The potential cooling within the cold pool increases for both increasing lapse rates as well as increasing dryness (and the lowness in θ_e) at mid levels.
- ▶ In general, the potential strength of the rear-inflow jet increases for increasing amounts of instability (CAPE) in the environment.

Rear-Inflow Jet: Strength



- ▶ The magnitude of the vertical wind shear is yet another contributor to the strength of the rear-inflow jet.
- ▶ Stronger shear tends to strengthen the RIJ by producing enhanced lifting at the leading edge of the system, which leads to a stronger, more continuous FTR ascending current.

Rear-Inflow Jet: Strength



- ▶ The result is that more warm air is transported aloft, enhancing the generation of horizontal vorticity, which enhances the magnitude of the RIJ. A strong FTR current also tends to lead to a stronger cold pool as well, since stronger convection leads to stronger downdrafts.

Rear-Inflow Jet: Affecting Squall Line Evolution

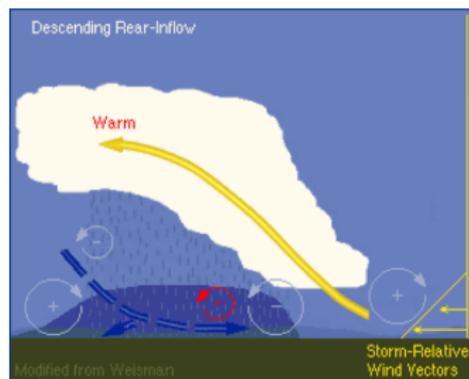
Generally, the rear-inflow jet entrains additional mid-level dry air into the rainy downdraft, further strengthening the cold pool. Two overall scenarios may then evolve.

- ▶ Descending RIJ
- ▶ Elevated RIJ

Rear-Inflow Jet: Affecting Squall Line Evolution

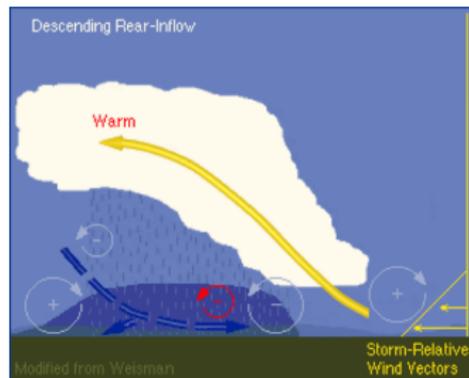
Descending Rear-Inflow

- ▶ If the buoyancy gradients associated with the warm air aloft are weaker than those associated with the rear flank of the cold pool, then the rear-inflow jet descends and spreads along the surface further back in the system.
- ▶ In this case, the negative horizontal vorticity associated with the rear-inflow jet is of the same sign as that being produced by the leading edge of the cold pool.



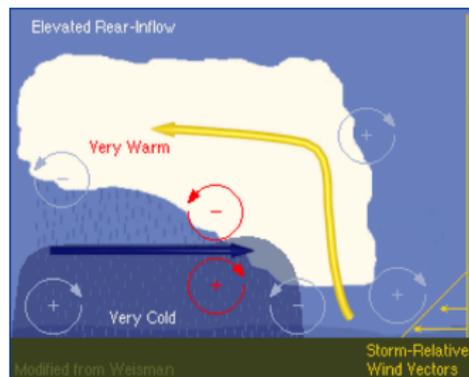
Rear-Inflow Jet: Affecting Squall Line Evolution

Descending Rear-Inflow



- ▶ The resultant vorticity interaction makes the effective $c/\Delta u$ ratio even larger, forcing the system to tilt even further upshear and continue to weaken.
- ▶ This is the most commonly observed scenario, occurring in environments with relatively weak shear and/or weak CAPE.

Rear-Inflow Jet: Affecting Squall Line Evolution



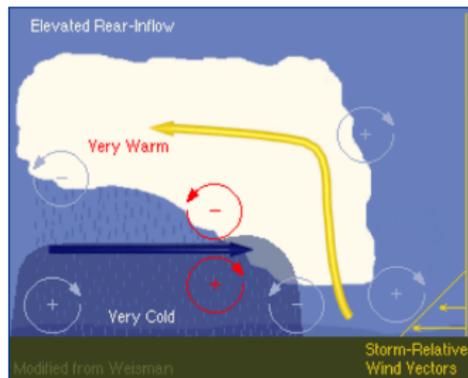
Elevated Rear-Inflow

- ▶ If the buoyancy gradients aloft are strong relative to the cold pool below, the rear-inflow jet tends to remain more elevated and advances closer to the leading edge of the system.

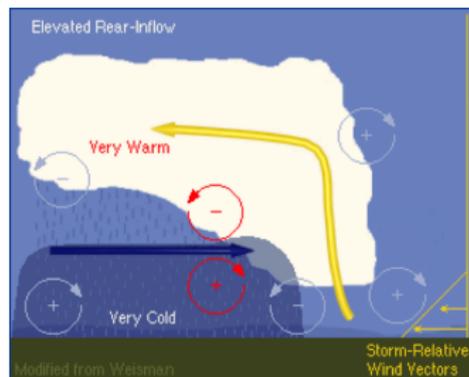
Rear-Inflow Jet: Affecting Squall Line Evolution

Elevated Rear-Inflow

- ▶ The horizontal vorticity produced by the speed shear below the rear-inflow jet is now of the same sign as the environmental shear. The resultant vorticity interaction then reduces the net impact of the cold pool circulation, bringing $c/\Delta u$ closer to the optimal ratio of 1, enhancing the leading-line convective updrafts and creating a more vertically erect structure.



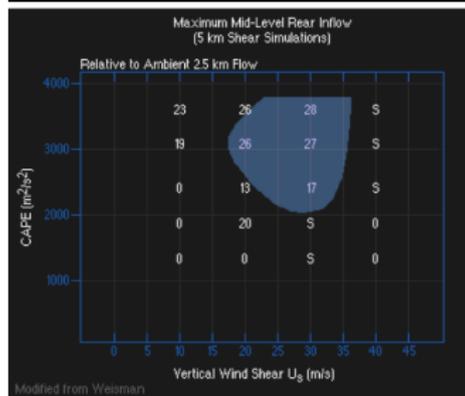
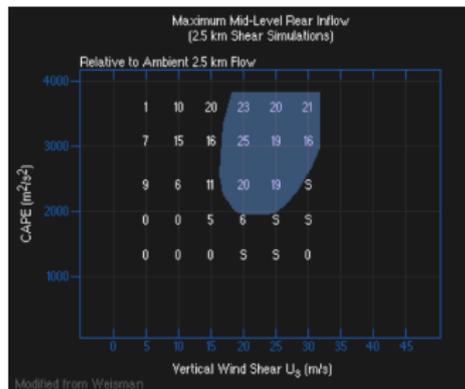
Rear-Inflow Jet: Affecting Squall Line Evolution



Elevated Rear-Inflow

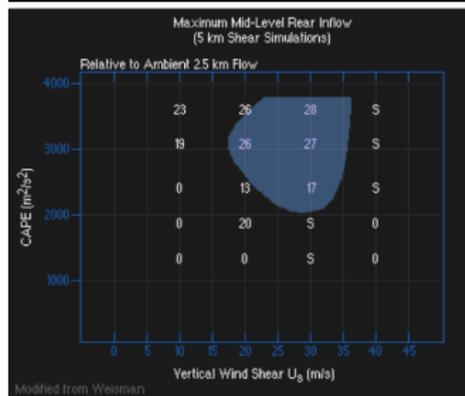
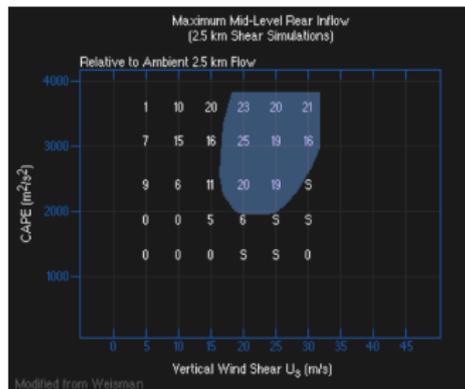
- ▶ This scenario occurs in environments with relatively strong shear and/or large CAPE and is especially associated with the development of severe bow echoes.

Rear-Inflow Jet: Strength Limits



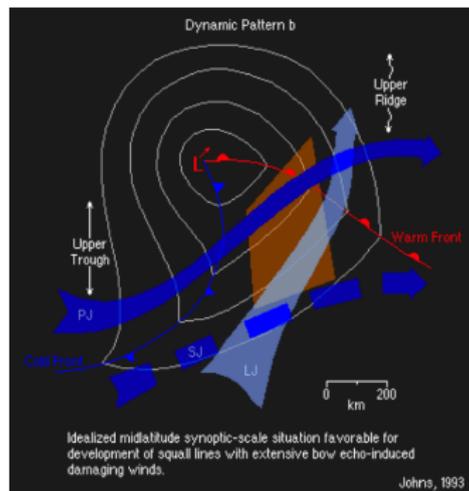
- ▶ Observations and modeling studies suggest that rear-inflow jets vary in strength from a few ms^{-1} for weak systems, to 10-15 ms^{-1} for moderately strong systems, to 25 to 30 ms^{-1} for the most severe systems such as bow echoes. These RIJ strengths are relative to storm motion, *i.e.*, actual ground-relative winds may be much stronger.

Rear-Inflow Jet: Strength Limits



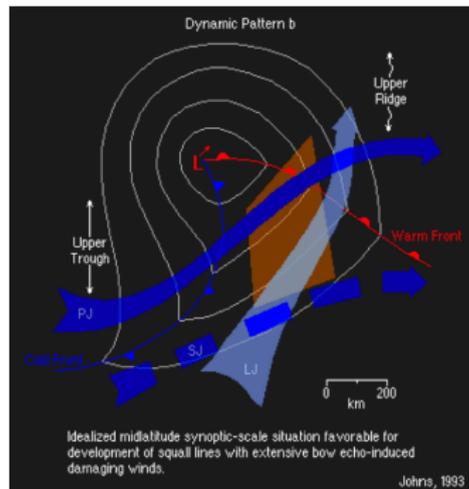
- ▶ Weisman (1992) quantified the dependence of rear-inflow jet strength on vertical wind shear and buoyancy for numerically simulated convective systems and confirmed that rear-inflow strength increases for increasing CAPE and increasing vertical wind shear.

Rear-Inflow Jet: Large-Scale Causes



- Imagine a synoptic pattern like this idealized scenario that is commonly associated with severe squall lines including bow echoes (Johns, 1993). For a squall line developing in the brown threat area, we can see that stronger flow in the region of the polar jet would enhance the rear-inflow jet associated with either the squall line or an embedded bow echo developing in the northern portion of the area.

Rear-Inflow Jet: Large-Scale Causes



- ▶ Additionally, if the mid-level storm-relative winds are significantly stronger behind a squall line, these enhanced winds can also contribute to the generation of the rear-inflow jet, especially when the squall line is expanding rearward to produce a large stratiform precipitation region.
- ▶ Of course, enhancements in the large-scale wind field behind the squall line need not be present for the production of a significant rear-inflow jet.

Rear-Inflow Jet: Summary

- ▶ During the mature stage of an MCS, the convective cells spread rearward transporting warm air aloft. The surface cold pool also extends rearward due to the rearward expanding rainfield.
- ▶ The juxtaposition of the warm air aloft over a cold pool produces lower pressure at mid levels, leading to mid-level convergence. The flow that converges in from the rear of the system at mid levels is known as the rear-inflow jet.
- ▶ The formation of the RIJ can also be explained by the horizontal buoyancy gradients at the back edge of the system, which generate a vertically stacked horizontal vorticity couplet that induces the rear-inflow jet.

Rear-Inflow Jet: Summary

- ▶ The strength of the RIJ is directly related to the strength of those buoyancy gradients, i.e., the relative warmth of the FTR current and the relative coolness of the cold pool.
- ▶ The RIJ strength is also affected by the strength of the vertical wind shear. Stronger shear produces enhanced lifting at the leading edge of the system, which leads to a stronger FTR current and enhanced warm pool.
- ▶ In weak shear, lower CAPE environments, the warm pool aloft tends to be weaker than the cold pool. In this case, the RIJ descends further back in the system.

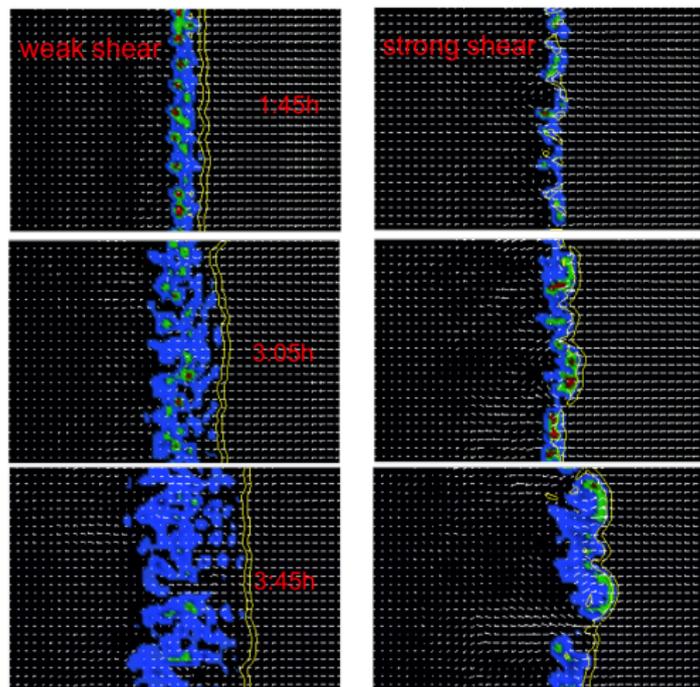
Rear-Inflow Jet: Summary

- ▶ In stronger shear/higher CAPE environments, the warm pool aloft tends to be comparable to the cold pool. This keeps the RIJ elevated until much closer to the leading line convection. This is usually the case with severe bow echoes.
- ▶ Storm-relative RIJ strengths vary from a few ms^{-1} for weak systems, to 10-15 ms^{-1} for moderately strong systems, to 25 to 30 ms^{-1} for the most severe systems, such as bow echoes.
- ▶ In general, RIJ strength increases for increasing CAPE and increasing vertical wind shear.

Model Simulations of Quasi-2D Squall Lines

- ▶ Simulations are presented which characterize a weak-shear scenario, a strong-shear scenario, and a scenario with strong shear at 45° to the line. The amount of CAPE for all was 2200 J/kg .
- ▶ The weak-shear simulation is run in an environment with 10 ms^{-1} of shear over the lowest 2.5 km AGL, with constant winds above 2.5 km, and demonstrates a squall line that tilts upshear and weakens by 3-4 h into its evolution.
- ▶ The stronger-shear simulation is run in an environment with 20 ms^{-1} of shear over the lowest 2.5 km AGL, and demonstrates a squall line which maintains its strength through the full 6 h of the simulation.

Model Simulations of Quasi-2D Squall Lines



Horizontal cross section at .5 km. The fields shown include reflectivity, storm relative winds, and an updraft contour where $w > 1.5 \text{ ms}^{-1}$ (in yellow). Spacing for wind vectors is 6 km.

OH LOOK



IT'S SPRING BREAK O'CLOCK