4B.6

WHAT IS RKW THEORY?

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1. INTRODUCTION

"RKW Theory" is the nickname for the concepts presented by Rotunno, Klemp, and Weisman in the 1980s. Their work was originally presented as "A Theory for Squall Lines" (Rotunno et al. 1987); see Fig. 1a. The title of the work was modified slightly to "A Theory for Strong, Long-Lived Squall Lines" for the peer-reviewed journal article, Rotunno et al. (1988, hereafter RKW88); see Fig. 1b. As a matter of fact, the term "strong, long-lived" appears nowhere in RKW88 other than the title.

Like all scientific concepts, RKW Theory has been revised and refined by subsequent studies. Perhaps the most significant revisions to RKW Theory came in the article by Weisman and Rotunno (2004, hereafter WR04), although according to WR04 the "basic interpretations of the RKW theory are reconfirmed" by their study. Some other studies have challenged this conclusion by WR04 (e.g., Stensrud et al. 2005). Considering that RKW Theory has been revised over time, some of this disagreement may be attributable to how one defines the term "basic interpretations."

This article reviews the core concepts of RKW Theory, and particularly those that have withstood scrutiny over the years. Aspects of RKW Theory that have not held up to scrutiny — and thus comprise the *revisions* noted above — are discussed later in this article. It is argued herein that if an extremely brief description of RKW Theory is necessary, then the phrase "A Theory for Squall Line Structure" is probably most suitable.

2. A BRIEF REVIEW

As noted in the first paragraph of RKW88, their study was motivated by a large set of three-dimensional numerical simulations that were initialized with a broad range of environmental shear profiles. Most of these results were reported in separate articles (Weisman and Klemp 1986; Weisman et al. 1988, hereafter WKR88). A novel result from these studies — and one that still stands today — is that an impressively broad range of convective structures can be produced by changing *only* the environmental shear profile in idealized numerical model simulations.

The RKW88 article focused on what the authors determined to be the "essential mechanisms" (p. 463) behind these different squall-line structures and their evolution in these simulations. Obviously the environmental shear is an essential element of any explanation because the initial shear was the only change in the various simulations. The other key element identified by RKW88 was the evaporatively cooled air near the surface, i.e., the cold pool. Identification of these two elements — shear and cold pool — was not a new idea. In fact, most of the Introduction of RKW88 was devoted to a review of previous explanations for how cold pools and environmental wind shear could affect squall line structure.

Of particular note was the article by Thorpe et al. (1982, hereafter TMM82). They analyzed two-dimensional simulations of squall lines in which 0–2.5 km AGL wind shear was held fixed, but the wind shear above 2.5 km was varied in intensity (from strongly negative to strongly positive). They found that certain measures of intensity, such as surface precipitation rate, were maximized when the initial shear above 2.5 km was set to zero. TMM82 argued that this particular shear profile allowed the cold pool to remain nearly stationary relative to the deep precipitating convection, thereby allowing evaporative cooling to continuously reinforce the cold pool. RKW88's schematic of the TMM82 theory is reproduced herein as Fig. 2. According to TMM82, the "optimum" (pg. 742) set of conditions that lead to this favorable situation is likely a function of shear, CAPE, evaporation rate, and perhaps other parameters.

Motivated by the TMM82 results, RKW88 examined a similarly designed set of simulations with environmental shear restricted to the lowest 2.5 km AGL. Like TMM82, RKW88 found that certain measures of squall-line intensity could be *maximized* (in other words, *optimized*) for a certain value of shear that is confined to low levels. The physical interpretation put forth by RKW88 was quite different from TMM82, though, and forms the basic premise of RKW Theory.

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3. THE BASIC PREMISE OF RKW THEORY

One novel aspect of RKW Theory — that seems to be mostly overlooked in subsequent studies on cold pools — is that in the absence of wind shear, cold pools are generally bad for convection. In the words of RKW88, cold pools are "inimical to updrafts" (pg. 477). The reason is illustrated in Fig. 3a herein; cold pools in unsheared and unstratified environments induce an overall circulation (as shown by blue streamlines in Fig. 3a) in which near-surface environmental air is accelerated horizontally over the top of the cold pool. This rearward acceleration, and the *negative* tendency to vertical velocity that arrests upward displacements, can "inhibit deep vertical penetration of the air which [the cold pool] displaces" (pg. 466). So although cold pools can lift air to saturation, the *complete flow field* (i.e., the "circulation" induced by the cold pool) will act against further lifting.

A second aspect of RKW Theory — an element that was well documented at the time — is that in the absence of cold pools, environmental wind shear is generally bad for convection (at least for ordinary convection that is not rotating, i.e., for non-supercellular convection). The reason is that updrafts tilt downshear under the influence of shear-updraft interaction processes (Fig. 3b). This downshear tilt is also inimical to convection because downdrafts can cause transport of dry mid-level air into the inflow layer, and also because downshear-tilted updrafts lose energy to the mean flow (particularly for two-dimensional convection) (e.g., Lilly 1979).

The primary insight of RKW Theory is that these two negative affects can counteract each other on the downshear side of cold pools. That is, the tendency to accelerate air over the top of the cold pool is counteracted by the tendency to accelerate air away from the cold pool on its downshear side. Hence *cold pools in sheared environments can be favorable for deep convection* and, furthermore, sheared cold pools can produce much deeper lifting than is possible by a cold pool without shear (Fig. 3c).

These concepts have stood the test of time. It is now widely acknowledged, at least conceptually, that cold pools in sheared environments induce deeper, stronger lifting than cold pools in the absence of shear (all else being nearly equal, such as the distribution of cold air) — but only on their downshear side.

4. APPLICATION TO SQUALL LINES

The term "squall line" is not used in Section 3 herein. The reason is that the core concepts of RKW Theory are based primarily on cold pool (i.e., gravity current) dynamics. The application to squall lines, however, is obvious given the tendency for many squall lines to produce surface-based cold pools. RKW88 viewed the primary role of cold pools as being a "trigger" for continuously developing convective cells. In contrast, some previous studies argued that squall lines were composed of special, extraordinarily long-lived updrafts. In other words, RKW88 viewed squall line convective regions as areas where *new* deep precipitating convection was continuously initiated in roughly the same system-relative region throughout time. Further studies with numerical models and Doppler radars have since found that both viewpoints have some merit (although extraordinarily long-lived updrafts seem to require an additional dynamical mechanism, like a rear-inflow jet, which is discussed later). Nevertheless, the particular viewpoint of RKW88 that the downshear-side of cold pools is especially favorable for triggering convection is widely supported by theoretical, numerical, and observational evidence.

RKW88 and WKR88 further showed how these concepts could explain the *structure* of squall lines. In cases where the tendency to sweep air over the cold pool exceeds the tendency for updrafts to lean downshear, then most precipitation falls on the upshear side of the surface gust front; see Fig. 4a. This type of squall line is now commonly referred to as a trailing stratiform system. When the opposite situation occurs, and the tendency for updrafts to lean downshear is stronger, then precipitation can fall on the downshear side of the surface gust front, which is commonly referred to as a leading stratiform squall line; see Fig. 4b. RKW88 also hypothesized a state in which these two effects roughly offset each other leading to essentially upright convective cells roughly above the surface gust front; this structure was referred to as the "optimal" structure because, in principal, the updraft is not inhibited by the cold pool or the environmental shear.

5. THE QUANTITATIVE CRITERION

The qualitative reasoning in the previous two sections, which forms the basic premise of RKW Theory, was reinforced by RKW88 through an analysis of the governing equations for fluid flow. They utilized the relevant vorticity equation for two-dimensional (x-z) flow, although the same results can be obtained using momentum and mass-continuity equations. The centerpiece was their control-volume analysis in their section 4c that yields a "quantitative criterion" (p. 477) for the two competing effects discussed above. Actually, RKW88 presented *two* control volume analyses, as illustrated in Fig. 5 herein.

The first control-volume analysis was for a cold pool in the absence of environmental shear (Fig. 5a). This situation was analyzed several times in previous decades, most notably by von Kármán (1940) and Benjamin (1968) [see, e.g., the review by Klemp et al. (1994)]. By basing their analysis on the horizontal vorticity equation, RKW88 added the additional insight that "the net generation of negative vorticity within the volume is just balanced by the export of negative vorticity out the downstream side" (p. 478). That is, while zero vorticity enters on the right side of the control volume (because the flow is not sheared), there *is* export of vorticity on the left side of the control volume (at the top of the cold pool at height H) and this vorticity is generated within the control volume via baroclinic processes near the edge of the cold pool. This analysis sets the stage for the second control-volume analysis.

When environmental shear is added to the analysis, there is now an import of horizontal vorticity on the right side of the control volume, as shown in Fig. 5b herein. From examination of their squall-line and gravity-current simulations, RKW88 noted that, with shear, the flow could turn upwards, instead of flowing over the top of the cold pool (as discussed in Section 2 above). Thus the second control volume analysis is based on a hypothesized "optimal state" where the flow is turned exactly into the vertical and exits the control volume in a "vertically oriented jet." The physical interpretation that arises from this control-volume analysis is that "the import of the positive vorticity associated with the low-level shear just balances the net buoyant generation of negative vorticity by the cold pool in the volume" (p. 478). In other words, when the rate of baroclinic vorticity generation near the edge of the cold pool is equal in magnitude to the (horizontal) flux of vorticity from the oncoming environmental air, then it is possible to have a vertically oriented jet as illustrated in Fig. 5b. The quantitative criterion that emerges from this analysis (i.e., a quantification of the concepts above) is

$$\Delta u = c \qquad (1)$$

where $\Delta u \equiv u_{R,d} - u_{R,0}$ is the net change in horizontal velocity along the right side of the control volume (a quantitative measure of shear intensity), and $c^2 \equiv 2\int_0^H (-B_L)\,dz$ where B_L is buoyancy on the left side of the control volume (a quantitative measure of cold pool intensity). So a vertically oriented jet can occur when the intensity of near-surface environmental shear equals the intensity of the cold pool, or $c/\Delta u = 1$.

Although the quantitative criterion $c/\Delta u = 1$ is technically only derived for one flow state by RKW88 (the one shown in Fig. 5b), subsequent analysis of several squall-line simulations by WKR88 showed that the value of $c/\Delta u$ was consistent with squall-line structure in the way that would be expected from the underlying physical interpretation. That is, for $c/\Delta u > 1$ the cold pool has more effect than the environmental shear and thus upshear-leaning systems develop (Fig. 4a), whereas for $c/\Delta u < 1$ the cold pool has a weaker effect than the environmental shear and thus downshear-leaning systems develop (Fig. 4a).

RKW88 also noted how the *time dependence* of overall squall-line evolution in their simulations could be explained by these concepts. That is, although the quantitative criterion was derived under the assumption of steady flow, the resulting quantitative criterion is nevertheless applicable to temporally evolving flows. Early in the life cycle of idealized squall line simulations, there is no cold pool (or a very weak cold pool). Hence $c/\Delta u < 1$ and updrafts tilt downshear (Fig. 6a). In simulations where the cold pool intensified sufficiently, such that $c/\Delta u \approx 1$, the updrafts became essentially upright (Fig. 6b). Further increases in cold-pool intensity, such that $c/\Delta u > 1$, then led to the upshear-tilted state with a trailing-stratiform region (Fig. 6c). This conceptual model of squall-line evolution was further supported quantitatively by WKR88 and Weisman (1992).

6. THE OPTIMAL STATE

As noted by WR04, some studies in the atmospheric science literature have interpreted the "optimal state" where a cold pool balances shear ($c/\Delta u = 1$) as a "necessary" state to support squall lines (WR04, p. 381). This is an incorrect interpretation because the optimal state is merely one point in a continuum from cold-pool-dominated systems on one end (Fig. 4a) to shear-dominated systems on the other end (Fig. 4b).

Lingering confusion over this issue probably arises from what is now widely considered to be an overemphasis on the need to be near the optimal state ($c/\Delta u \approx 1$) to maintain *strong* squall lines in RKW88's simulations. Specifically, in their numerical simulations, there was a tendency for squall lines to weaken considerably, after some point, unless $c/\Delta u$ was near unity. This result was first called out by Fovell and Ogura (1989, hereafter FO89) who noted that their simulations of sub-optimal ($c/\Delta u < 1$) squall lines (with a different numerical model) showed no such rapid weakening. FO89 correctly implicated the small domain used by RKW88, which can cause the open lateral boundary conditions to play a role in system evolution, and is probably too small to represent the expansive stratiform regions that can form in long simulations. (This issue is addressed further in Section 7.1 below.)

Controversy over the optimal state concept has also arisen from results by RKW88 and WKR88 (and, it should be added, by TMM82, who first proposed the idea) showing that some measures of squall-line intensity are *maximized* in numerical simulations when squall-line updrafts are nearly upright and shear is confined to low levels. For example, RKW88 noted that updraft velocity was strongest, and WKR88 noted that condensation was greatest, when $c/\Delta u \approx 1$ and shear was restricted to low levels. In their re-evaluation of RKW Theory, WR04 presented several other measures of squall-line intensity (including measures of surface wind speed to address concerns about squall-line severity) in support of the relevance of the optimal state to squall-line intensity. However, in their comments on WR04's study, Stensrud et al. (2005) noted that squall-line intensity was, in fact, not well explained by the ratio $c/\Delta u$ in WR04's broad set of simulations. Using results reported by WR04, Stensrud et al. (2005) found that some measures of intensity (like total rainfall) were maximized for $c/\Delta u \approx 0.5$, whereas other measures (like average surface windspeed) were maximized for $c/\Delta u \approx 1.8$. However, very shortly thereafter, Bryan et al. (2006) ran some of WR04's squall-line simulations with different numerical models and found that both rainfall and surface windspeed were maximized for $c/\Delta u \approx 1$. They found that WR04's simulations tended to over-predict c (compared to the other models) because their numerical model had a sink of heat at the surface due to the surface boundary condition in their vertical diffusion scheme. Bryan et al. (2006) thus concluded that "some of the criticisms of RKW theory's applicability to squall lines (e.g., Stensrud et al. 2005) are attributable to the numerical model used by RKW88 and WR04, but not necessarily to the theory itself."

7. REVISIONS TO RKW THEORY

All scientific concepts are revised as new evidence comes to light. RKW Theory is no different, although it seems like many recent studies on RKW Theory evaluate the original 1988 article without regards to these revisions. In this section, the most notable revisions to RKW Theory are explained briefly. Future studies that evaluate RKW Theory are encouraged to incorporate these revisions in their analysis.

7.1 *Squall-line longevity*

Very soon after the publication of RKW88, FO89 noted how the small size of the domain used by RKW88 and WKR88 caused some (but not all) of their simulated squall lines to weaken rapidly. As a consequence, RKW88 over-emphasized the need to have $c/\Delta u$ close to 1 in order to have a strong *and* long-lived squall line. (A squall line was certainly possible in RKW88's simulations without $c/\Delta u$ near 1, and their squall lines could be "strong" without $c/\Delta u$ near 1, but their squall lines were rarely "strong *and* long-lived" unless $c/\Delta u$ was near 1.) In their simulations, FO89 found that "the less than optimal condition ... causes the model storm to be weaker and more clearly multicellular, but at the same time one which is not necessarily fatal or terminal."

The squall-line simulations conducted by WR04 used a much larger domain than the simulations by RKW88/WKR88. Despite using the same numerical model and overall setup as these previous studies, WR04 found that *all* simulations — including one with no initial shear — maintained a quasi-steady intensity until the end of their 6-hour simulations. Consequently, WR04 concluded that the abrupt demise in the RKW88 simulations (especially for weak shear) was "more of a numerical artifact than a physical effect." These results led Bryan et al. (2006, p. 2773) to conclude that system longevity can no longer be considered a part of RKW Theory.

To be fair, RKW Theory "does not focus merely on system longevity" (Rotunno et al. 1990, p. 1031) but rather focuses on processes that promote strong *and* long-lived squall lines. The no-shear case presented by WR04 may be "long-lived" but was noted to be "highly disorganized" (p. 369) and was clearly not strong; in fact, the zero-shear case was one of only 3 simulations, out of 44 presented by WR04, that did not produce a severe (≥ 26 m s^{-1}) surface wind gust. So, considering *longevity with reference to strength and structure* (to modify a phrase from WR04, p. 380), then the primary revision to RKW Theory seems to be a broadening of the $c/\Delta u$ values that are considered most favorable, from something *near* 1 in RKW88, to something more like 0.5–3 [based on the WR04 and Bryan et al. (2006) simulation results].

7.2 *An Extension to the RKW88 Quantitative Criterion*

In an investigation of the role played by convectively generated rear-inflow jets, Weisman (1992) revisited the RKW88 control volume analysis to include flow in the cold pool. Note that the term "flow in the cold pool," which refers to non-zero gust-front-relative flow *within* the cold air, is quite different from the term "circulation induced by the cold pool," which refers to the *complete flow field* spanning the leading edge of the cold pool (as shown by blue streamlines in Fig. 3); some studies (e.g., Xu and Moncrieff 1994) seem to have incorrectly conflated these concepts.

Weisman (1992) followed the control volume analysis exactly as in RKW88 and assumed a state wherein the environmental flow turned upward and exited as a vertically oriented jet (i.e., the optimal state), but also allowed for flow on the left side of the control volume (blue arrows in Fig. 7). This methodology allows for vorticity *within* the cold pool associated with rear-inflow jets and leads to the solution

$$\Delta u^2 = c^2 - \Delta u_J^2 \qquad (2)$$

where $\Delta u_J^2 \equiv u_{L,H}^2 - u_{L,0}^2$. Comparing with the original quantitative criterion (1), and assuming c has the same value, then a rear-inflow jet with $u_{L,H}^2 > u_{L,0}^2$ (the typical situation for observed elevated rear-inflow jets) allows for the vertically oriented jet structure to occur at a lower value of environmental shear Δu. In other words, with a rear inflow jet in the cold pool, updrafts can become upright for a weaker environmental shear than without the rear inflow jet (all else being nearly equal).

Weisman (1992, p. 1840) further noted that for typical values of c^2 the strength of the rear inflow jet must exceed roughly 10 m s^{-1} to have a "significant impact," and thus "the RKW theory alone (without the addition of the rear-inflow current) may still be sufficient to characterize the evolution of most observed convective systems." Indeed, in their study, WR04 concluded that the original quantitative criterion (1) "still provides a useful guide of overall system structure" (p. 376). Nevertheless, the relation (2) should technically be used for cases in which rear-inflow jets are important for squall-line structure.

7.3 *The Importance of Shear Above the Cold Pool*

A complicating issue for applying RKW Theory to real-data cases and numerical simulations is the depth over which to calculate Δu, or in other words, how exactly to quantify environmental wind shear. Conceptually, RKW Theory considers the layer over which cold pools interact with environmental wind shear to be most important. RKW88 concluded (p. 477): "Since cold pools are located at low levels, the shear can promote convection only when restricted to low levels" and that "... it is the actual shear within the air that makes contact with the cold pool that is influential."

Since the publication of RKW88, several observational and numerical modeling studies have shown that mid- and upper-level shear can also be influential on squall lines (e.g., Fovell and Dailey 1995; Coniglio et al. 2006). Several dynamical explanations for this result have been advanced over the years. Here, two dynamical explanations are reviewed briefly.

First, the flow induced by vorticity (i.e., the circulation associated with vorticity, as illustrated by blue streamlines in Fig. 3) extends beyond the vorticity distribution itself. From a fluid dynamics perspective, the flow is represented by a streamfunction ψ, horizontal vorticity is $\eta \equiv \partial u/\partial z - \partial w/\partial x$, and the relevant elliptic equation has the form $\nabla^2 \psi = \eta$ (e.g., Section 2 of WR04). Because of the nature of elliptic equations, there can be "action at a distance" effects in which the flow beyond the edge of the cold pool is influenced by vorticity located only at the cold pool edge. Numerical simulations by WR04 confirm this interpretation. (Identical conclusions are reached from a consideration of perturbation pressure; i.e., negative buoyancy within the cold pool can induce accelerations beyond the confines of the negatively buoyant air). Hence, WR04 noted that the emphasis on the shear layer that "makes contact with the cold pool" as emphasized by RKW88 (p. 477) was "technically incorrect" (WR04 p. 366). This led WR04 to revise RKW Theory's qualitative arguments from being restricted to the depth of the cold pool (i.e., H) to some layer "in close proximity to" the cold pool, which seems to be roughly 1.5–2 times the depth of the cold pool based on WR04's gravity-current simulations. To be clear, WR04 still considered shear confined to the cold-pool layer as being *most* favorable, as in RKW88; the primary revision was a deepening of the shear layer that *can be* favorable for lifting on the downshear side of cold pools.

Secondly, squall lines typically occur in conditionally unstable environments, and so updrafts release latent heat that is not represented by the density-current analyses in the RKW88 article. Among studies that have examined this process, the studies by Fovell and Tan (1998, hereafter FT98) and Parker and Johnson (2004, hereafter PJ04) are probably the most comprehensive. FT98 noted that convective updrafts generate vorticity through baroclinic processes, and because updrafts extend through mid and upper levels of the troposphere then shear throughout the troposphere can be influential on squall-line structure. [As a matter of fact, RKW88 *did* consider the baroclinically generated vorticity along cloud edges in their conceptual model (particularly in their Section 4a); nevertheless, this effect is not represented in RKW88's "quantitative criterion", (1).] FT98 advanced a revised conceptual model of RKW Theory in their Section 4b in which updrafts interact with shear over the depth of the troposphere. This is essentially the same process discussed by WR04 on their pgs. 372–373, although WR04 focused on negative buoyancy associated with condensate above the cold pool, whereas FT98 focused on positive buoyancy associated with updrafts. In addition, PJ04 further considered the kinematic effects of shear-updraft interaction (i.e., that updrafts tend to tilt downshear), which can further contribute toward an "overturning mean updraft" that is strongly influenced by shear in mid and upper levels of the troposphere. PJ04 further noted how convective updrafts are typically transient (unlike the cold pool) and their effects may be greatly underestimated by analysis of time-mean flow fields.

The exact depth over which to quantify environmental shear is currently an active area of research that particularly impacts the severe storms forecasting community (e.g., Coniglio et al. 2012). Nevertheless, the relevant depth according to RKW Theory should not be restricted to the depth of the cold pool, even for idealized gravity currents in isentropic environments.

8. BEYOND RKW THEORY

For various reasons, RKW Theory does not apply to every squall line. According to RKW88: "The observations also showed a number of cases that don't fit easily within the *weltansicht* of squall lines offered herein" (pg. 483). (The word *weltansicht* means "world view" or "outlook on life.") Among the various review articles and textbooks on squall lines (and, more generally, on mesoscale convective systems), the one by Fritsch and Forbes (2001, hereafter FF01) offers an especially helpful conceptual model. FF01 refer to convective systems that "rely on the formation of surface-based moist-downdraft-generated cold pools" as "type-2 events" (FF01, p. 335); see Fig. 8b herein. RKW Theory applies most directly to these types of convective systems.

The other type of system reviewed by FF01 — their "type-1 events" — are associated with frontal overrunning by nocturnal low-level jets; see Fig. 8a. In their view, certain combinations of mesoscale and/or synoptic-scale processes could act to organize mesoscale convective systems in which RKW Theory "is not as readily applicable" (FF01, p. 338).

Perhaps other types of "events" could be added to this list, such as convective lines forced by strong cold fronts, or linear bands of convection associated with balanced vortices (e.g., tropical cyclones and mid-level mesoscale convective vortices). Furthermore, even among squall lines in which cold-pool dynamics are important, those with significant *three-dimensional* structure, such as the "parallel stratiform" type system (e.g., Parker 2007), require consideration of processes not considered by RKW Theory. Clearly, RKW Theory cannot explain all linear convective phenomena. As such, the beginning of RKW88's title — "A Theory" — should *not* be interpreted as "The Only Theory" for squall lines.

9. SUMMARY

The concepts presented by RKW88 — more commonly known as RKW Theory — are based on two fundamental processes: 1) the tendency for cold pools (in the absence of shear) to limit vertical motion because air is swept horizontally over the top of the cold pool (Fig. 3a); and 2) the tendency for shear to limit vertical motion in (non-supercellular) updrafts because shear causes updrafts to tilt (Fig. 3b). The key insight of RKW Theory is that these two processes counteract each other on the downshear side of cold pools, and hence cold pools in sheared environments can be favorable for deep moist convection (Fig. 3c). These "basic interpretations" (WR04) of RKW Theory have been supported by numerous studies. Nevertheless, some aspects of RKW Theory have been revised based on studies conducted since RKW88; see Section 7 herein.

RKW Theory applies most directly to gravity currents (or cold pools in isentropic environments) but it has clear relevance to squall lines that have surface-based cold pools. The most robust application to squall lines seems to be squall line structure: when cold-pool intensity (measured by the parameter c) exceeds environmental wind-shear intensity (measured by the parameter Δu) then squall-line updrafts typically tilt upshear and a trailing stratiform region usually develops (Fig. 4a). When shear intensity exceeds cold-pool intensity, then squall-line updrafts typically tilt downshear and a leading stratiform region usually develops (Fig. 4b). If an extremely short description of RKW Theory is needed, then it is probably best to use the phrase "A Theory for Squall Line Structure."

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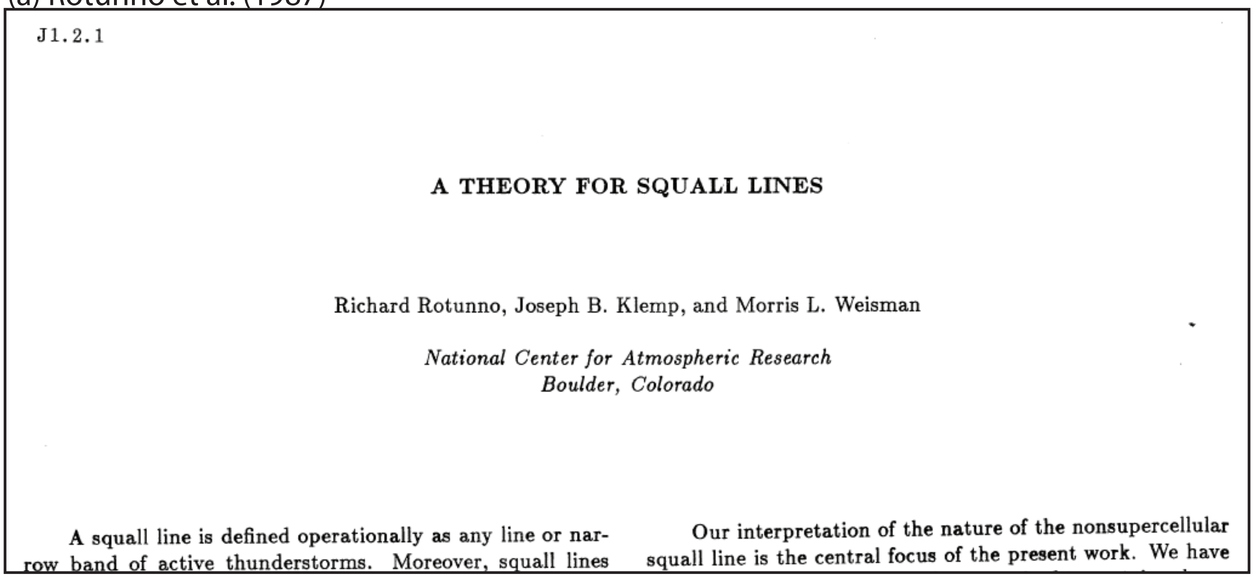
(a) Rotunno et al. (1987)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A THEORY FOR SQUALL LINES

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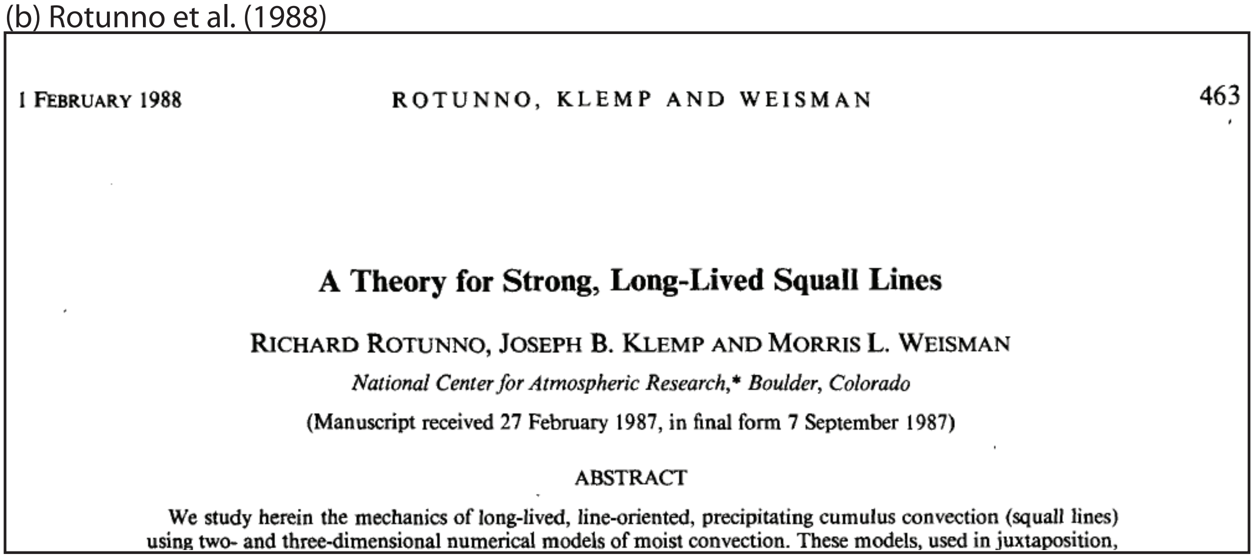
A squall line is defined operationally as any line or narrow band of active thunderstorms. Moreover, squall lines

Our interpretation of the nature of the nonsupercellular squall line is the central focus of the present work. We have

(b) Rotunno et al. (1988)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A Theory for Strong, Long-Lived Squall Lines

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ABSTRACT

We study herein the mechanics of long-lived, line-oriented, precipitating cumulus convection (squall lines) using two- and three-dimensional numerical models of moist convection. These models, used in juxtaposition,

FIG. 1: (a) A screen capture of the preprint paper for the 3rd Conference on Mesoscale Processes (21–26 August 1987). (b) A screen capture of the of the peer-reviewed journal article RKW88.

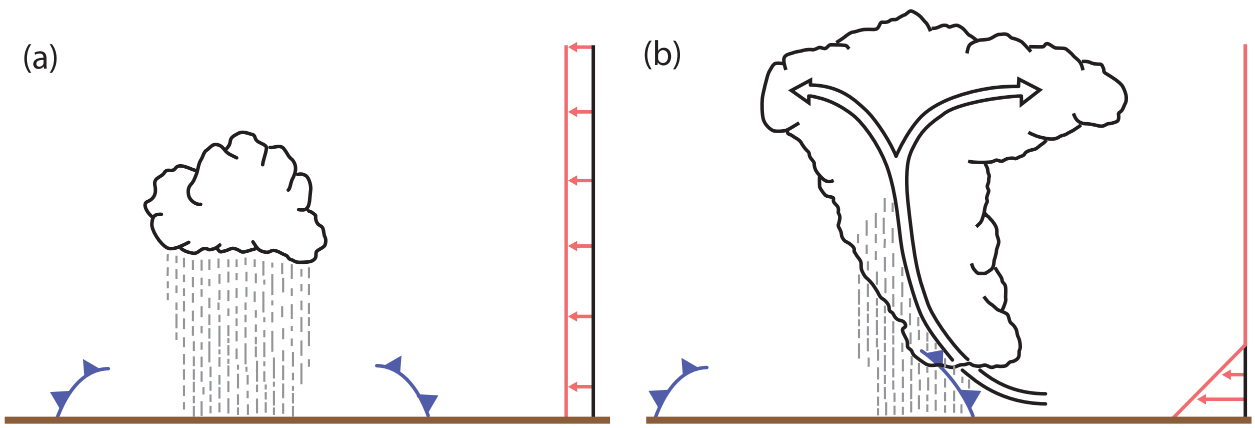

FIG. 2: Thorpe et al. (1982, pp. 741–743) argued that (a) without low-level shear, the rain-produced cold pool propagates away from the cloud above, whereas (b) with low-level shear, the cold pool remains beneath the cloud and produces a long-lived cell. (Figure and caption adapted from RKW88, their Fig. 5.)

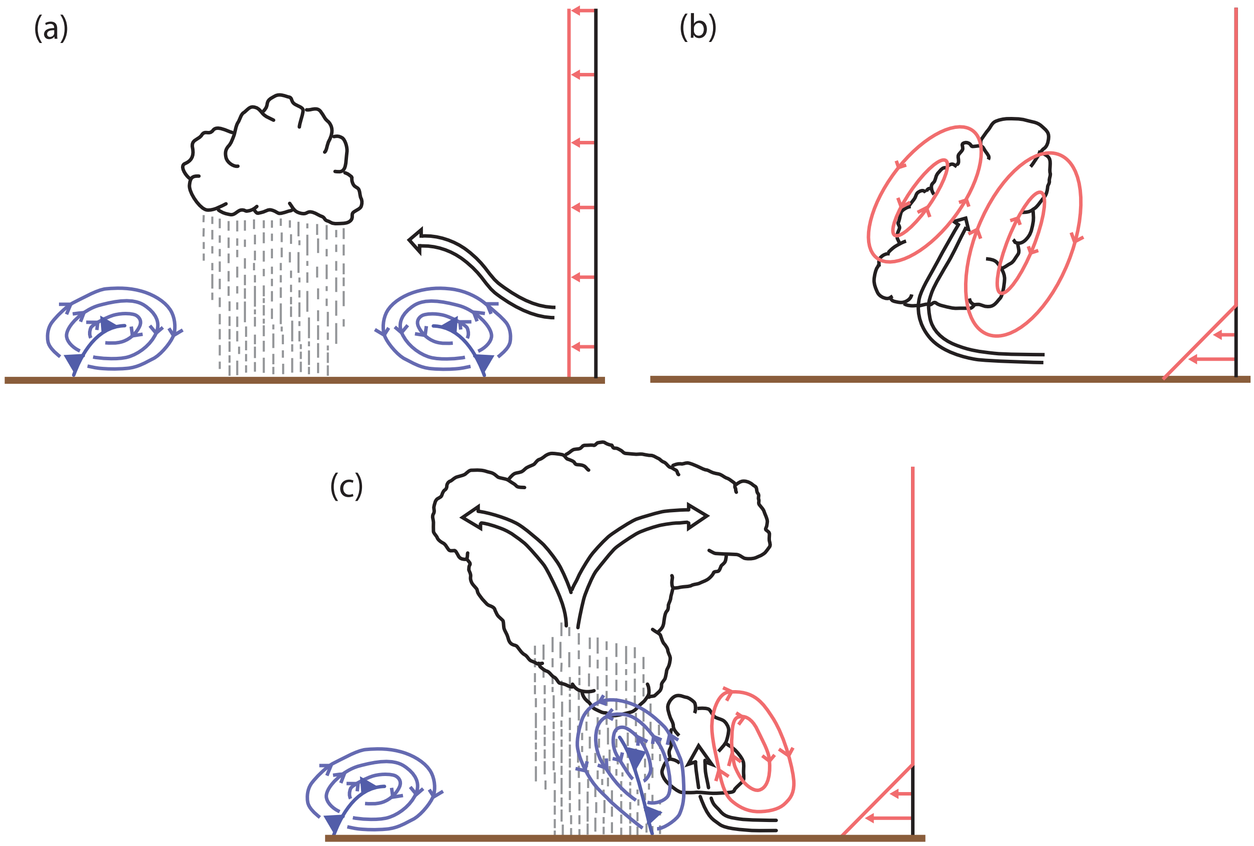

FIG. 3: In RKW88, they argued that (a) without low-level shear, the circulation induced by a spreading cold pool (blue streamlines) inhibits deep lifting and so cannot trigger a cell. (b) For an updraft in shear (without a cold pool), the thermally created vorticity together with the shear vorticity lead to a circulation (red streamlines) that tilts downshear. (c) The presence of low-level shear counteracts the circulation induced by the cold pool and promotes deep lifting that triggers new cells. (Figure and caption adapted from RKW88, their Figs. 5 and 18.)

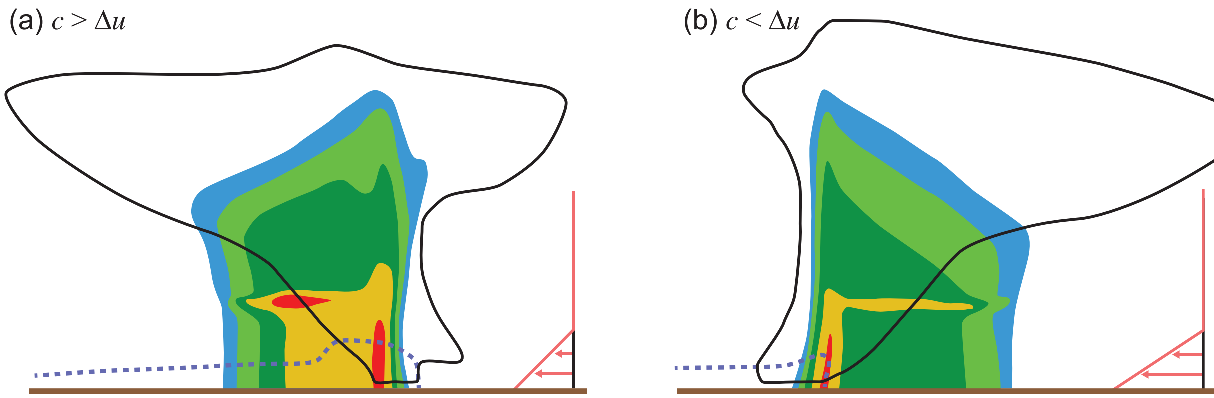

FIG. 4: Typical structures associated with (a) cold-pool-dominated squall lines ($c > \Delta u$); and (b) shear-dominated squall lines ($c < \Delta u$). Black contours illustrate cloud boundaries, color shading denotes reflectivity, and blue-dashed lines illustrate cold pool boundaries.

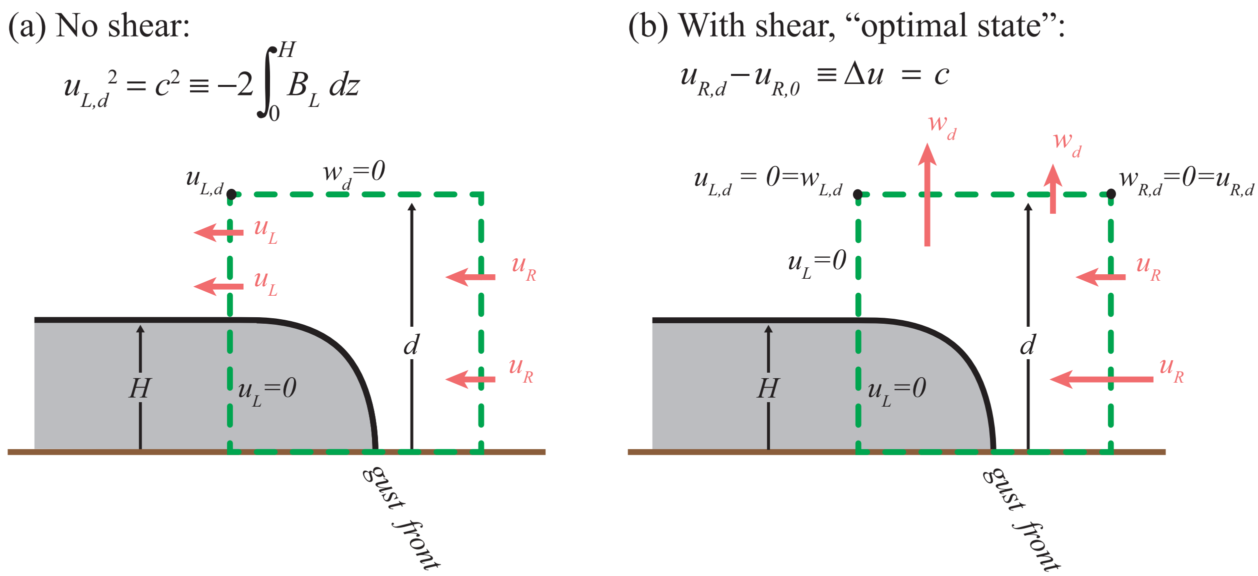

FIG. 5: Conceptual models for the two control-volume analyses presented in RKW88. (a) A gravity current without environmental shear. The dashed green box denotes the control volume (CV), u_R is the gust-front-relative flow on the right side of the CV, u_L is the gust-front-relative flow on the left side of the CV, H is the depth of the cold pool on the left side of the CV, and d is the depth of the CV. The gust-front-relative flow is zero within the cold pool on the left side of the CV. (b) As in (a) except for a gravity current with low-level environmental shear in the "optimal state where the low-level flow is turned ... to exit as a vertically oriented jet" (RKW88, pg. 478). The gust-front-relative flow on the right side of the control volume (u_R) is a function of z and the vertical velocity at the top of the control volume (w_d) is a function of x. The gust-front-relative flow at the top-corners of the CV (black dots) is zero.

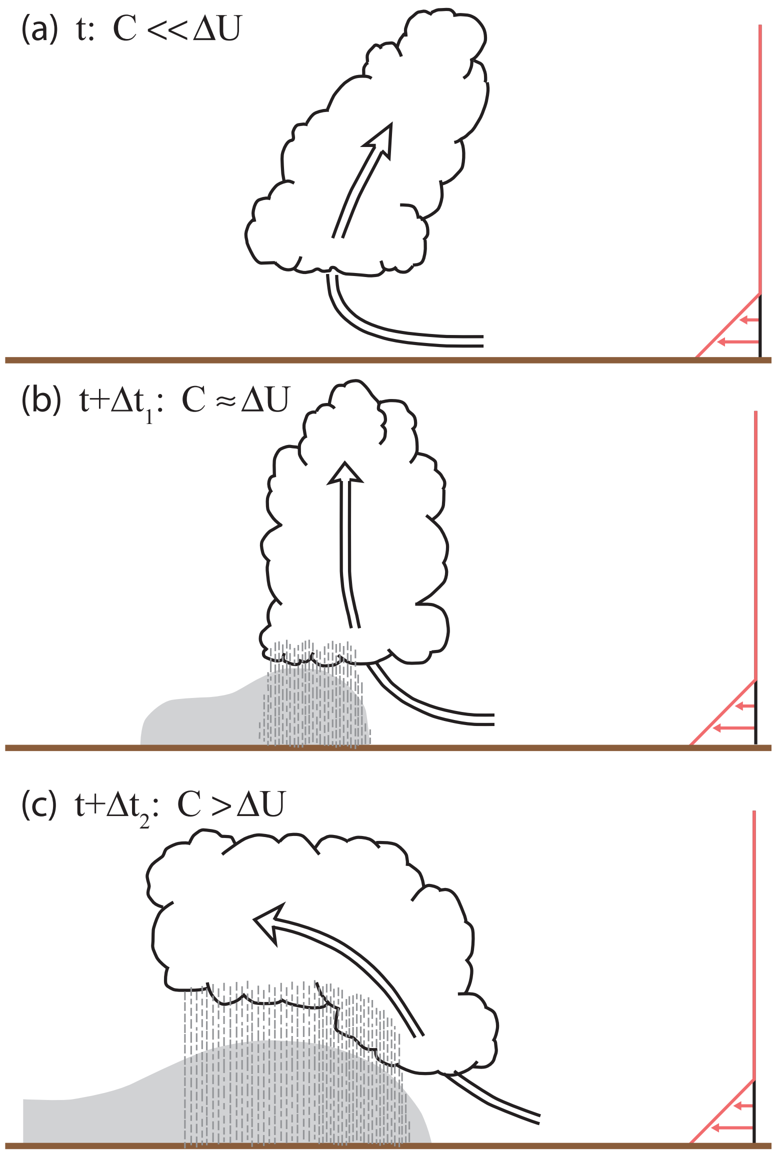

FIG. 6: Three stages in the evolution of simulated squall lines. (a) An initial updraft leans downshear in response to the ambient vertical wind shear. (b) The circulation generated by the storm-induced cold pool roughly balances the ambient shear, and the system becomes upright. (c) The cold-pool circulation overwhelms the ambient shear and the system tilts upshear. (Figure and caption adapted from WR04.)

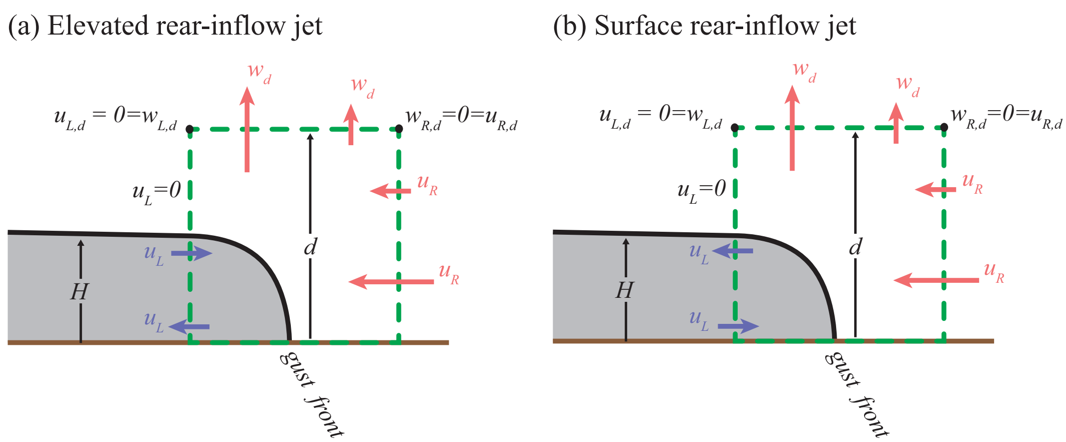

FIG. 7: Schematic illustrating the extension of RKW88's analytic solution for the "optimal state" by Weisman (1992) that accounts for gust-front-relative flow in the cold pool (blue arrows). For (a) the gust-front-relative rear-inflow is elevated, and for (b) the rear-inflow is near the surface.

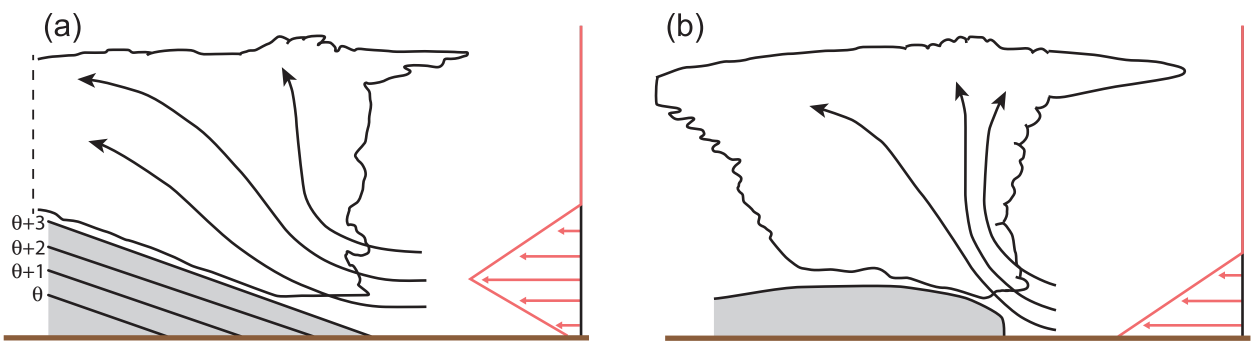

FIG. 8: Convective-mesoscale feedback processes in contrasting environments. (a) Low-level jet overruns a frontal zone ("type-1 system"), and (b) low-level wind-shear and cold pool ("type-2 system"). [Figure and caption adapted from Fritsch and Forbes (2001).]