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# AN ASSESSMENT OF CONVECTIVE SYSTEM STRUCTURE, COLD POOL PROPERTIES, AND ENVIRONMENTAL SHEAR USING OBSERVATIONS FROM BAMEX

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## 1. INTRODUCTION

Utilizing theory, idealized numerical model studies, and limited observations, Rotunno et al. (1988) and Weisman et al. (1988) advanced a theory to explain the retriggering of cells along cold pools in squall lines. Now often referred to as "RKW Theory," the concept also has been found to explain the overall structure of simulated squall lines and many types of simulated mesoscale convective systems (MCSs). The theory focuses on two opposing processes: the strength of the system's surface-based cold pool, measured by $C$; and the low- to mid-level vertical wind shear in the environment, measured by $\Delta U$. When $C < \Delta U$, cells that form along the gust front lean downshear (Fig. 1a). Numerical models typically produce a leading stratiform structure when this state occurs. On the other end of the spectrum, when $C > \Delta U$, cells lean upshear (Fig. 1b). Model simulations typically produce a trailing stratiform system when this state occurs. In a recent reevaluation of the theory, Weisman and Rotunno (2004) conclude that the relative strengths of the cold pool and environmental shear have "a profound effect on system organization," and "thus, represents a highly useful concept for describing overall system properties."

There seems to be no comprehensive study that has evaluated this relationship in observed MCSs. One main reason has been the lack of soundings in and near MCSs. At least two soundings are needed for the analysis: one in the undisturbed environment, and one in the system's cold pool. The operational rawinsonde network has insufficient spacing and launch rate for this purpose.

The Bow Echo and MCV Experiment (BAMEX) was designed partly to address this observational void. During BAMEX, about 700 soundings were obtained using research platforms. Almost all soundings were within or near MCSs, or within mesoscale vortices generated by MCSs. Thus, the sounding data collected during BAMEX provide a unique opportunity to assess RKW Theory.

## 2. METHODOLOGY

### *2.1 Data*

This study uses the BAMEX composite sounding dataset interpolated to constant 5 mb levels, provided by the Joint Office for Science Support (JOSS). Documentation for this dataset is available at the JOSS web site http://www.joss.ucar.edu/bamex/dm/archive. This dataset includes all available atmospheric soundings, including dropsondes from the Learjet, rawinsondes from mobile ground-based platforms, and rawinsondes from the operational network operated by NOAA.

Radar images for this study are generated from the WSI NOWrad product on a 2 km grid with 15 min temporal resolution. A companion study that composited soundings locations relative to the convective system (Ahijevych et al. 2004) was utilized in the selection of soundings for the analysis herein.

### *2.2 Sounding selection*

To evaluate the theory, two soundings are required for the analysis: one that is representative of the environment; and one that measures the cold pool of the MCS. Different criteria are used to select these two classes of soundings.

For the environmental sounding, the sonde must have sampled the low-level air that comprised the inflow to the system. Fortunately, many environmental sound-

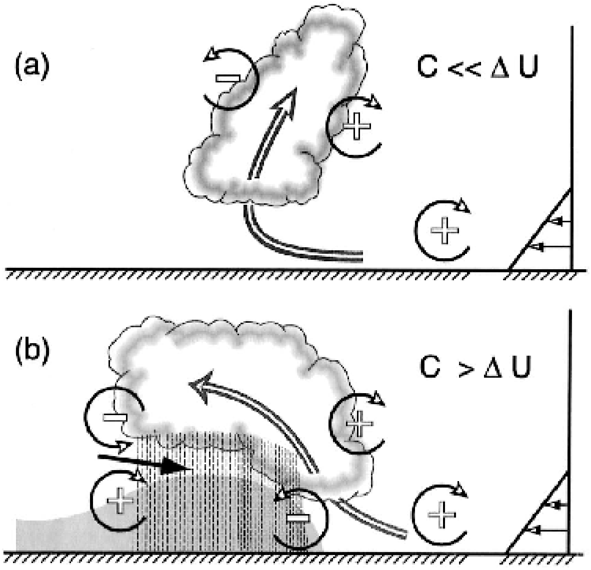

Fig. 1. A schematic illustrating system structure compared to cold pool intensity ($C$) and low- to mid-level environmental shear ($\Delta U$). (a) When $C < \Delta U$, updrafts tilt downshear, and a leading stratiform structure develops. (b) When $C > \Delta U$, updrafts tilt upshear, and a trailing stratiform structure develops. Adapted from Weisman and Rotunno (2004).

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ings were available to choose from, most of them within 100 km of the convective line, and < 2 h before system passage. For this initial investigation, one environmental sounding was chosen for each of the cold pool soundings; no attempt is made at this time to measure possible heterogeneity in the environment.

The cold pool soundings were initially selected if they probably sampled the convective cold pool. This selection was based on subjective comparisons of sonde location, system movement, and system structure. The list was further reduced by examination of the soundings themselves; a candidate case was excluded if it appeared to contain observational errors, or if the sounding did not contain sufficient data for the analysis. The final list for the analyses herein contains 26 cold pool soundings from 9 IOPs. All of these soundings were within 35 km of the convective line, with a mean distance from the convective line of 18 km, and a median distance of 15 km.

This methodology contains considerable uncertainty, even considering the unprecedented spatial and temporal resolution of the BAMEX dataset. Each sounding represents *local* conditions that are not necessarily representative of the entire system. On the other hand, for MCSs that had multiple cold pool soundings, the calculations of $C$ agree reasonably well (within ~20%).

### 2.3 Analysis methods

Cold pool intensity is measured by $C$, defined by

$$C^2 = 2\int_0^H (-B)\,dz\,, \qquad (1)$$

where $z$ is height, $H$ is the cold pool depth, and $B$ is buoyancy, calculated herein by

$$B = g\left(\frac{\theta-\bar{\theta}}{\bar{\theta}} + 0.61\left(q_v - \bar{q}_v\right)\right). \qquad (2)$$

In (2), $g$ is the gravitational acceleration, $\theta$ is potential temperature, and $q_v$ is water vapor mixing ratio. The overbars indicate the environmental conditions, from the environmental sounding, and all other calculations are based on the cold pool sounding. The effects of frozen and liquid hydrometeors on $B$ are necessarily neglected, because these quantities are not available from the soundings. The value for $H$ is the height above ground at which $B$ is first observed to be > –0.01 m s$^{-2}$.

A measure of the surface potential temperature difference ($\Delta\theta$) across the gust front was also obtained from the two soundings, based on the surface conditions reported in the sounding data.

Environmental shear is measured by the system-perpendicular wind variation ($\Delta$U) between specified layers, measured by height above ground ($z$). The calculations for U, obtained at $z$ = 0, 2.5, 5, and 10 km, use an average of all available data points for the 25 mb centered on that level. This averaging was used to smooth small-scale variations in the wind profile.

System structure was determined subjectively from the radar images. Four system classifications are considered herein: 1) intensifying or mature trailing stratiform (TS); 2) weakening trailing stratiform (W-TS); 3) leading stratiform (LS); and 4) parallel stratiform (PS). This classification scheme is based on that of Parker and Johnson (2000). The TS systems were subdivided into separate categories to account for systems that were sampled during different phases in the system development. The PS and TS cases analyzed herein were all mature and long-lived during the time of observation.

In summary, this study analyzes 9 TS systems (with 22 soundings), one LS system (with 2 soundings), and one PS system (with 2 soundings). A total of 15 environmental soundings are used.

## 3. COLD POOL PROPERTIES

For the cases selected herein, $C$ varies from 3 to 37 m s$^{-1}$, and $H$ varies from 0.5 to 5 km (Fig. 2). For most TS cases, $H$ is very close to the melting level, especially for cases measured during a system's mature state.

The PS system (blue dots) had the weakest and shallowest cold pool, even though these observations were within ~10 km of the convective line. These observations were from the southern end of the PS system. A deeper, stronger cold pool would be expected farther north, where the hydrometeors are being transported by strong along-line flow.

The change in potential temperature across the gust front at the surface, $\Delta\theta$, has been proposed as a proxy for $C$ (Evans and Doswell 2001). However, an analysis of $\Delta\theta$ compared to $C$ from the BAMEX observations does not support this proposal (Fig. 3). Analyses often show a complex profile of $B$ as a function of height. For

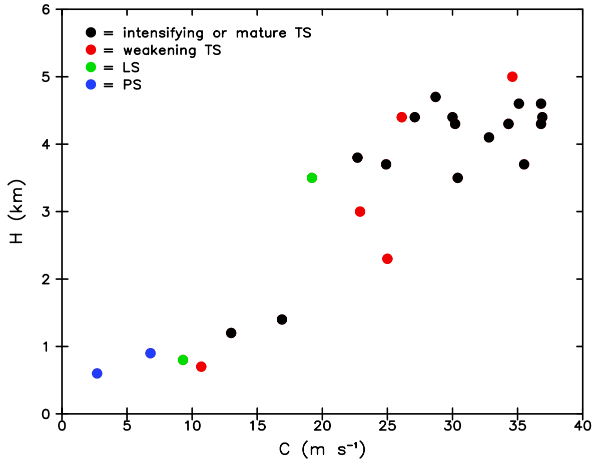

Fig. 2. $H$ versus $C$.

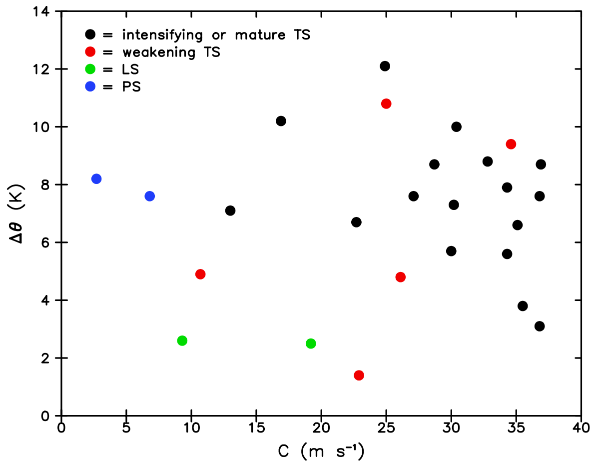

Fig. 3. Surface $\Delta\theta$ versus $C$.

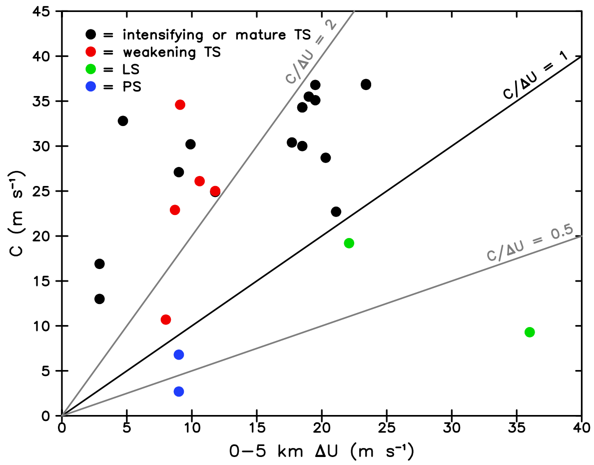

Fig. 4. $C$ versus $\Delta U$.

example, $B$ often decreases with height in the first km above the ground, which possibly reflects a warming from surface fluxes in the MCS cold pools. Furthermore, nocturnal events often show evidence of strong radiative cooling near the surface in environmental soundings. These two effects — low-level cooling in the environment and low-level warming in the cold pool — reduce $\Delta\theta$, but have a lesser effect on $C$, a vertically integrated measure.

## 4. EVALUATION OF RKW THEORY

Analyses of $C$ compared to 0–5 km $\Delta U$ provide support for the theory that these two parameters play a major role in overall system structure (Fig. 4). However, the parameter space may not have been well sampled during BAMEX, which was concerned mostly with the trailing stratiform archetype.

The two observations from the PS case (blue dots) have $C$ / $\Delta U$ ratios < 1, owing to the shallow cold pools at the southern end of the line. Given the inherent three-dimensionality of PS lines — because the cold pool has significant along-line variability — and the assumption of two-dimensionality within RKW Theory, it seems that PS structure cannot be explained by RKW Theory alone.

The two observations from the LS case (green dots) both have a $C$ / $\Delta U$ ratio < 1, as predicted by RKW Theory. Of course, two observations from one system limits the overall scope of this analysis. All that can be said at this time is that the observations are consistent with the theory.

All TS cases have a $C$ / $\Delta U$ ratio > 1, which is also consistent with RKW Theory. There is some suggestion that weakening systems (red dots) tend to have $C \gg \Delta U$, while mature and intensifying systems (black dots) tend to have a $C$ / $\Delta U$ ratio closer to 1.

The three TS points with the weakest $\Delta U$ (< 5 m s$^{-1}$) were all from one case, and all were observed at an early stage in the system's evolution. Interestingly, this system was relatively short lived, and underwent a rapid decay stage where the cold pool surged ahead of the convection. This evolution is also consistent with RKW Theory, which predicts shorter-lived systems when low- to mid-level shear is weak.

Overall, this analysis supports — or, at least, does not contradict — the main element of RKW Theory: i.e., that system structure is strongly influenced by cold pool intensity and low- to mid-level environmental shear. The only exception is the PS case, which contains significant along-line variability, and thus cannot be explained solely by the two-dimensional assumptions inherent in RKW Theory.

## 5. SUMMARY

Analysis of observations collected during BAMEX is ongoing. This investigation highlights some of the opportunities provided by the high temporal and spatial resolution of the BAMEX dataset.

To our knowledge, this is the first attempt using observations to evaluate the main element of RKW Theory; i.e., that system structure is strongly influenced by the relative intensities of a system's surface-based cold pool, and the low- to mid-level environmental shear. All cases analyzed herein support the theory, except for the parallel stratiform system.

### *Acknowledgments*

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## REFERENCES

Ahijevych, D., G. Bryan, C. Davis, J. Knievel, S. Trier, and M. Weisman, 2004: System-relative distribution of atmospheric soundings obtained during BAMEX. Preprints, *22nd Conf. on Severe Local Storms*, Hyannis, MA, Amer. Meteor. Soc., CD-ROM, 5.6.

Evans, J. S., and C. A. Doswell III, 2001: Examination of derecho environments using proximity soundings. *Wea. Forecasting,* **16,** 329-342.

Parker, M. D., and R. H. Johnson, 2000: Organizational modes of midlatitude mesoscale convective systems. *Mon. Wea. Rev.,* **128,** 3413-3436.

Rotunno, R., J. B. Klemp, and M. L. Weisman, 1988: A theory for strong, long-lived squall lines. *J. Atmos. Sci.,* **45**, 463–485.

Weisman, M. L., and R. Rotunno, 2004: “A theory for strong long-lived squall lines” revisited. *J. Atmos. Sci.,* **61,** 361–382.

Weisman, M. L., J. B. Klemp, and R. Rotunno, 1988: Structure and evolution of numerically simulated squall lines. *J. Atmos. Sci.,* **45,** 1990-2013.