NOTES AND CORRESPONDENCE

Comments on "'A Theory for Strong Long-Lived Squall Lines' Revisited"

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1. Introduction

The recent paper by Weisman and Rotunno (2004, hereafter WR04) revisits their earlier study on the strength and longevity of squall lines in which an "optimal" state was proposed in which the relative strength of the circulation associated with the storm-generated cold pool and the circulation associated with the environmental shear are balanced. Through the use of an expanded set of numerical simulations at higher resolution and within a larger computational domain, and through the use of a simplified, two-dimensional vorticity–streamfunction model, WR04 (p. 381) claim to reconfirm their earlier results and conclude that "the relative strength of the cold pool and ambient shear has a profound effect on system organization over the entire range of environments considered, whether optimal or not, and, thus, represents a highly useful concept for describing overall system properties." Although we certainly agree that ambient shear is an important factor in the dynamics of squall lines, we examine more critically the importance of the relative strength of the cold pool and ambient shear to system organization and evolution. We also will show that their statement (p. 381) that "in cases when sufficient observations of system structure, cold-pool strength, vertical wind shear, etc., have been available, we believe that they have consistently confirmed the basic shear relationships discussed herein" is misleading.

This comment is subdivided into two main sections. The first section compares the results from WR04 with the available observations and other numerical simulations to see how well the WR04 theory is in agreement with what is observed. The second section examines the internal consistency of the conclusions in WR04. We conclude with a brief discussion on the utility of the optimality concept to meteorology.

2. Observational comparisons

WR04 first present results from a simplified, two-dimensional vorticity–streamfunction model that shows that the maximum vertical displacement of low-level air parcels occurs when only low-level shear is present in the environmental wind profile (their Fig. 5). However, a dimensional version of this figure (Fig. 1) motivates a different interpretation when combined with information on the typical environments of observed squall lines. To create this figure we assume a buoyancy of

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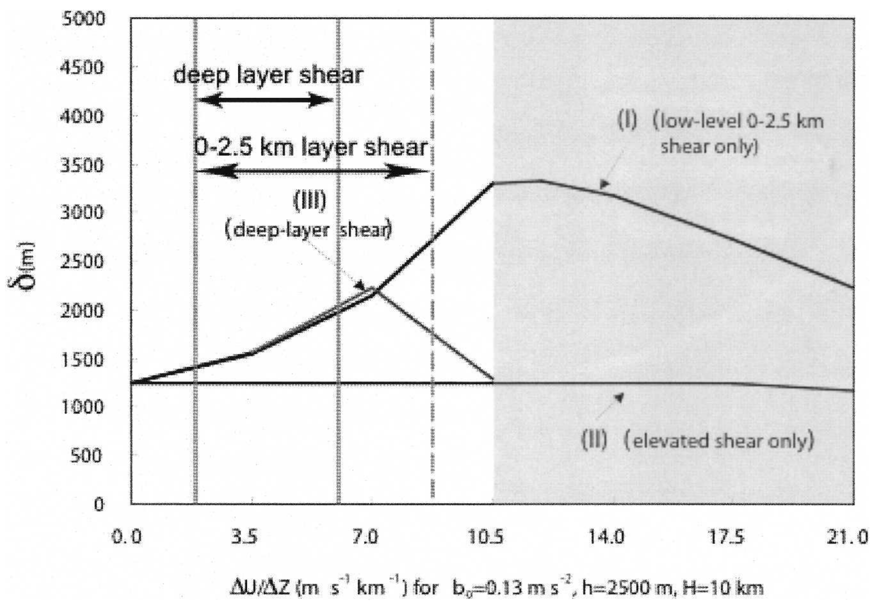

FIG. 1. Dimensional version of Fig. 5 from WR04, showing the maximum displacement δ (m) of low-level (<2500 m) air parcels for all experiments versus the mean wind shear (m s^{-1} km^{-1}). The solid line (I) is for the low-level 0–2.5-km shear-only simulations, the solid line (II) is for the elevated shear-only cases, and the dark gray line (III) is for the deep layer 0–10-km shear cases. The range of wind shear representing the middle 90% of the mean shear values from 91 observed severe squall lines is indicated by the gray vertical lines for deep layer shear (as defined in Fig. 2) and the 0–2.5-km shear. The shaded region to the right represents solutions that are for environments in which severe squall lines have been observed only once in our dataset.

-0.26 m s^{-2} (which yields a perturbation potential temperature of -8 K for the cold pool assuming an environmental temperature of 300 K), an initial depth of 5000 m for the block of cold air (which should lead to an eventual cold pool depth of ~2500 m according to WR04), and a domain depth of 10 km. These are reasonable values for many squall lines. Note that ΔU in Fig. 5 of WR04 can be replaced with $\Delta U/(2\Delta z)$ for easier interpretation and comparisons with their Figs. 6–9. Also note that colder cold pools would produce even larger dimensional shear values along the abscissa in Fig. 1 for the same value of dimensionless $\Delta U = 1$. For example, using a -16 K perturbation potential temperature for the cold pool (buoyancy of -0.52 m s^{-2}) leads to multiplying the shear values in Fig. 1 by 1.4.

In the idealized model, the amount of lifting seen in the deep layer shear (where the shear is distributed over the full 10-km domain depth) and low-level shear-only cases is nearly identical up to shears of 7 m s^{-1} km^{-1}, while for larger shears the low-level shear-only cases provide greater lifting (Fig. 1). However, it is equally important to consider the range of shear values from the observed environments of long-lived squall lines. Bluestein and Jain (1985) examine the environments of severe squall lines and find that the mean subcloud layer, pressure-weighted vertical wind shears for 40 cases is 8.2 m s^{-1} km^{-1}. Similarly, the mean pressure-weighted surface to 6 km shear is 3.9 m s^{-1} km^{-1}. For a 10-km-deep domain, the shear values depicted in Fig. 5 of WR04 are calculated over a layer that is 2500 m deep. This layer is deeper than the observed mean subcloud layer shear from Bluestein and Jain (1985), but shallower than 6 km. Therefore, a shear value somewhere between 3.9 and 8.2 m s^{-1} km^{-1} is probably the most reasonable to compare with Fig. 1, based upon the Bluestein and Jain results.

To obtain a more helpful comparison, 91 severe squall-line cases have been examined from the dataset of Coniglio et al. (2004) and their mean shear values along the squall-line motion determined from proximity soundings for various atmospheric layers (Fig. 2). All these long-lived squall-line cases are associated with horizontally continuous, intense, leading-line convective echoes, since WR04 (p. 377) state that "it is the ability to produce a more solid line of convective cells rather than supercells that is specifically addressed by RKW." [Here, RKW refers to the Rotunno et al. (1988) reference in WR04.] Results indicate that, when considering only the shear observed in the lowest 2.5 km,

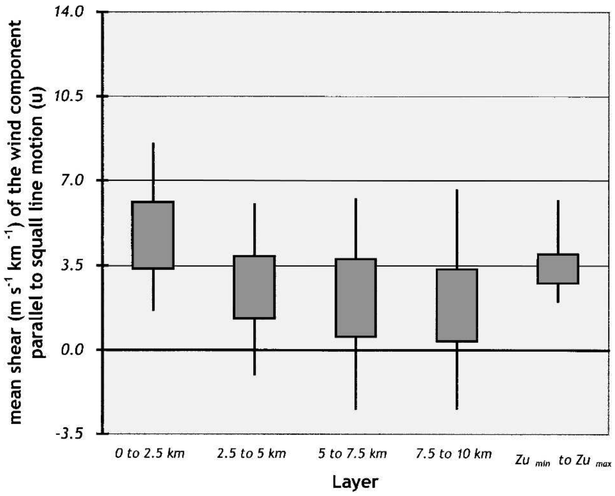

FIG. 2. The range of the mean shear (m s^{-1} km^{-1}) of the wind component parallel to squall-line motion (u) in various layers. The mean shear for each sounding is calculated by the difference in u between the two levels. The depth "$Zu_{\min}$ to $Zu_{\max}$" refers to the layer that is bounded by the minimum and maximum u for each sounding, and is usually 8–12 km deep. This depth is used to calculate the deep layer shear values depicted in Fig. 1. Boxes denote the 50% of the distribution between the 25th and 75th percentiles. The vertical lines extend to the 5th and 95th percentiles.

87% of the cases have mean shear values less than 7.0 m s^{-1} km^{-1}. An even larger percentage of the cases have mean shear values less than 7.0 m s^{-1} km^{-1} if the shear over the lowest 5 km is examined. However, as shown in Fig. 2, most of the squall-line cases have shears that extend over layers much deeper than 5 km, such that squall-line environments with only low-level shear are not observed frequently. When considering deep-layer shear (as defined in the caption of Fig. 2), over 96% of the observed cases in our dataset have mean shear values less than 7.0 m s^{-1} km^{-1}. Three conclusions can be drawn from these results. First, since most squall-line environments have environmental shear values less than 7.0 m s^{-1} km^{-1}, the lifting produced from deep-layer and low-level shear-only profiles is nearly identical for the majority of squall-line environments according to the simplified modeling results of WR04 (Fig. 1). Second, the environments of only a small number of squall lines are such that the low-level shear-only profile in WR04 is representative of the observed shear profile (Fig. 2). Third, mean shear values greater than 10.5 m s^{-1} km^{-1} in any layer are observed only once in association with the severe warm and cold season squall lines in our dataset, so most of the right-hand side in Fig. 1 (shaded in gray) has little relationship to the actual environments of most long-lived squall lines. It appears that these large shear values are just not observed regularly in the atmosphere in association with long-lived, severe squall lines.

The next section of WR04 discusses the results from their three-dimensional squall-line simulations. While the results are interesting, a missing—yet very important—piece of the puzzle is the observations. In their final section, WR04 state (p. 381) that comparing their results with observations "can be quite difficult, as observations are quite sparse" and later state that "cold pool characteristics are especially difficult to monitor over the lifetime of a system, and such input is critical for comparison with the above modeling results." Therefore, a simple method for testing the results of WR04 using routinely available observations, which can be used to sample many squall lines over their entire lifetime, is greatly desired. Since the most challenging aspect of comparing the results of WR04 to observations is indeed the cold pool parameter C [defined in their Eq. (10)], we use 300 two-dimensional cloud-scale model simulations to determine if a reasonable proxy can be found for C that can be easily observed. The cloud-scale model used is the National Severe Storms Laboratory Collaborative Model for Multiscale Atmospheric Simulation (NCOMMAS; Wicker and Wilhelmson 1995), run with warm rain processes only, and is very similar to the model used in WR04.

These two-dimensional cloud-scale model simulations are perturbed in both the thermodynamic and wind profiles from the runs discussed in WR04. The control thermodynamic profile around which the perturbations are made is the same as in WR04, while the control wind profile has 17.5 m s^{-1} of shear over the lowest 2.5 km and no shear above this height. Note that this environmental sounding does not have a low-level inversion and the level of free convection is low. Thus, deep lifting may not be necessary for convective retriggering in the simulations, as is also true in the runs reported in WR04. Random perturbations in wind speed, with standard deviations of up to 2.0 m s^{-1}, are specified on model levels at 2500-m vertical intervals and interpolated to the intervening model levels using a cubic spline. The thermodynamic profile is altered both by perturbing the exponential constant used to specify the relative humidity and by perturbing the specified temperature at the tropopause level. These two parameters affect the values of relative humidity and temperature throughout the troposphere [see Eqs. (1) and (2) in Weisman and Klemp (1982)]. The two sounding alterations yield perturbations in convective available potential energy with standard deviations of up to 550 J kg^{-1}. Convective inhibition in these perturbed soundings is not changed. Thus, the 300 perturbed simula-

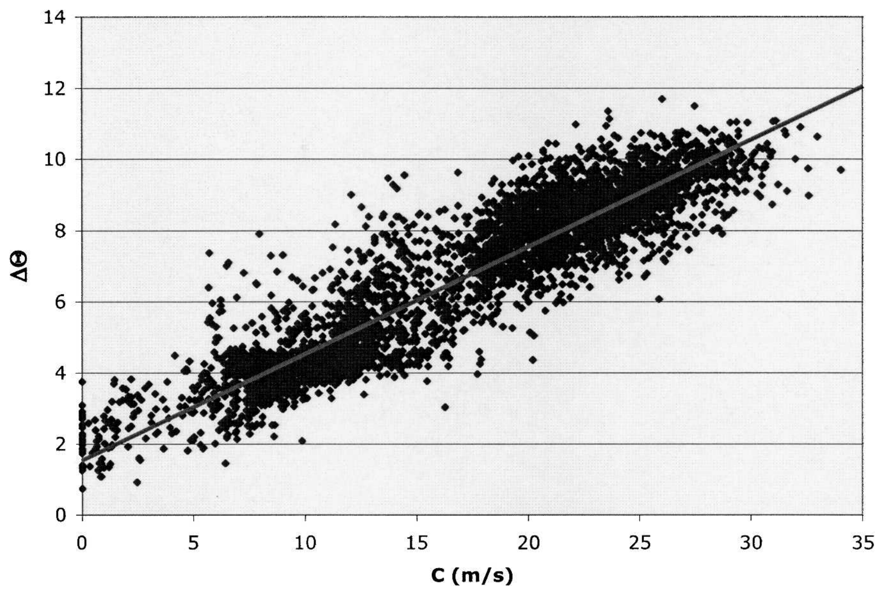

FIG. 3. Values of C vs the maximum difference in near-surface potential temperature from 300 NCOMMAS model simulations. Here C is calculated as described in Coniglio and Stensrud (2001). Line indicates the best least squares fit to the dataset. Data are extracted from the NCOMMAS runs at 30-min intervals, so more than 300 data points are available.

tions remain horizontally homogeneous, as in the control run, but use a slightly modified environmental sounding and wind profile for each run.

Evans and Doswell (2001) propose that the maximum difference in surface potential temperature across the outflow boundary can be used as a proxy for the cold pool parameter C. This hypothesis is tested in the two-dimensional model simulations by calculating C at a location 15 km behind the gust front and also calculating the maximum difference in near-surface potential temperature (i.e., the lowest model level) between this location and the environmental air just ahead of the gust front. This calculation is conducted using the model data every 30 min, and so captures the simulated squall lines across their entire life cycle. Results indicate that C is highly correlated with this maximum change in potential temperature across the gust front (Fig. 3), with a correlation coefficient r of 0.920. Thus, it appears that one can calculate a reasonable proxy for C from routinely available observations, with a root-mean-square error of approximately 3 m s^{-1}.

Evans and Doswell (2001) also show data from proximity soundings and surface observations for 67 derecho-producing convective systems and compare the observed, low-level environmental shear to the maximum difference in potential temperature across the convective system gust front. If we take these results from Evans and Doswell (2001), as depicted in their Fig. 17b, and convert the maximum difference in surface potential temperature across the gust front into a value for C based upon the NCOMMAS simulations, then a comparison between estimates of C based upon surface observations and 0–2-km wind shear from proximity soundings for long-lived, severe squall lines can be made (Fig. 4). Similar results are found if we use 0–3-km shear instead, or if we estimate C based upon a least squares fit to $\sqrt{\Delta\theta}$ (instead of $\Delta\theta$) using the data from the NCOMMAS simulations (r = 0.918). While Evans and Doswell (2001) did not explicitly examine the convective organization of the derecho-producing convective systems in their study, it is our experience that derecho-producing convective systems without continuous and intense leading-line convective cells are rare. Thus, if the cold pool strength–wind shear balance controls, or has a profound influence on, the strength and longevity of squall lines that have a more solid line of convective cells, then we would expect at least a hint of a linear relationship between C and environmental wind shear to be apparent from this dataset. However, Fig. 4 shows no such hint of a linear relationship. In fact, the correlation between C and the 0–2-km shear (ΔU) is -0.32 and the values of $C/\Delta U$ range from 0.12 to 11.7! Similar results are found using C and the shear between 0 and 3 km (not shown). Since the shear in squall-line environments decreases above 2.5 km (Fig. 2), it is difficult to believe that this lack of relationship between C and the environmental wind shear will change dramatically if calculated over 0–5 km. This

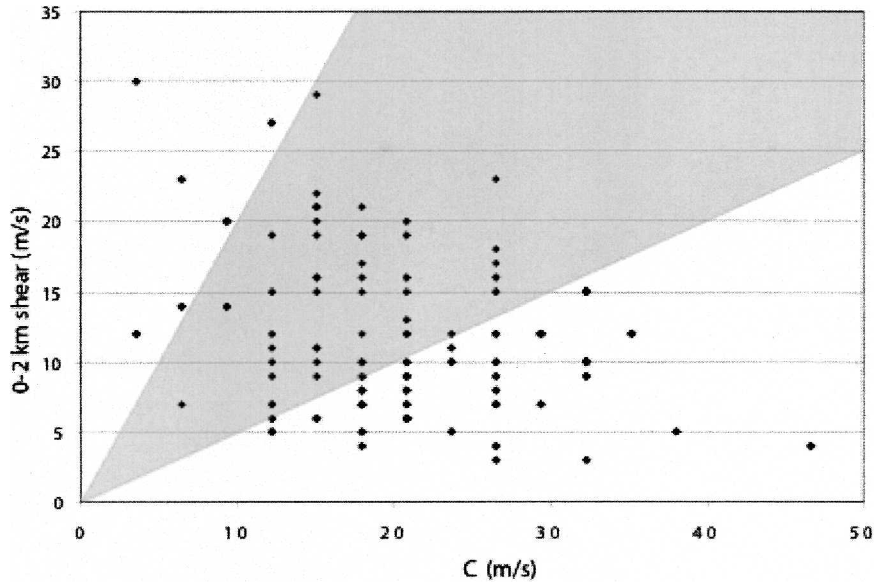

FIG. 4. Values of C (m s^{-1}) vs the 0–2-km wind shear (m s^{-1}) from observed severe squall-line cases. Here C is calculated from observed maximum differences in surface potential temperature across the gust front associated with severe squall lines (from Evans and Doswell 2001) that are converted to C using the best least squares fit to the dataset from the NCOMMAS model results as shown in Fig. 3. The 0–2-km wind shear is from proximity soundings described by Evans and Doswell (2001). The shaded region is where $0.5 \leq C/\Delta U \leq 2.0$.

leads us to question whether the value of $C/\Delta U$ has any relevance to the characteristics of observed squall lines. It certainly has no utility as a concept that can be used in the forecasting or nowcasting of squall lines when using standard observations that are available to forecasters.

3. Internal consistency

Another approach to testing the utility of the results of WR04 is to examine if the balance between cold pool and environmental shear circulations explains best the characteristics of the numerically simulated squall lines. Recall that the two-dimensional vorticity–streamfunction model results of WR04 show that there is deeper lifting of parcels at the leading edge of the density current when $C/\Delta U$ is close to 1, where C is related to the buoyancy of the cold pool and ΔU is now the difference in the environmental wind from the ground to 5 km above ground level. The layer over which ΔU is calculated was 2.5 km in their earlier study, but has been increased to allow for action at a distance (Davies-Jones 2002) and for the proposed ability of decaying rain cells in the 2.5–5-km layer to trigger new cells in an analogous way to the cold pool–shear interactions.

A comparison of the values of $\Delta U/C$ and ΔU from WR04's squall-line simulations (obtained from WR04's Table 1b) indicates that $\Delta U/C$ is highly correlated with ΔU (Fig. 5) with an explained variation R^2 of 0.965 in linear regression. (We used $\Delta U/C$ because $C/\Delta U = \infty$ in the no-shear cases). The means of ΔU and C are 14.09 and 19.91 m s^{-1}, respectively; the corresponding standard deviations are 9.25 and 2.10 m s^{-1}, respectively. Thus, the high correlation between $\Delta U/C$ and ΔU is due to the small variability in C. Consequently, it is impossible to tell from WR04's data whether the characteristics of the simulated squall lines are more a function of $\Delta U/C$ than of ΔU. For instance, the most erect modes of convection occur for $\Delta U/C \approx 1$ *and* for $\Delta U \approx 22$ m s^{-1}.

We performed quadratic regression on the quantities tabulated in WR04 to determine how much of the variability in total rainfall, total condensation, maximum vertical velocity ($w_{\max}$), maximum surface wind ($u_{0\max}$) and average surface wind ($u_{0\text{avg}}$) might be explained by $\Delta U/C$, ΔU, or C alone, and to see if the regression curves reveal optimal states for these variables. The explained variations are shown in Table 1. Total rainfall is strongly correlated with ΔU and $\Delta U/C$. However the regression curve for rainfall versus $\Delta U/C$ has a broad peak not at $\Delta U/C \approx 1$ but at $\Delta U/C = 1.9$ (not shown). Total condensation has the next highest correlations with the independent variables, but increases with all of

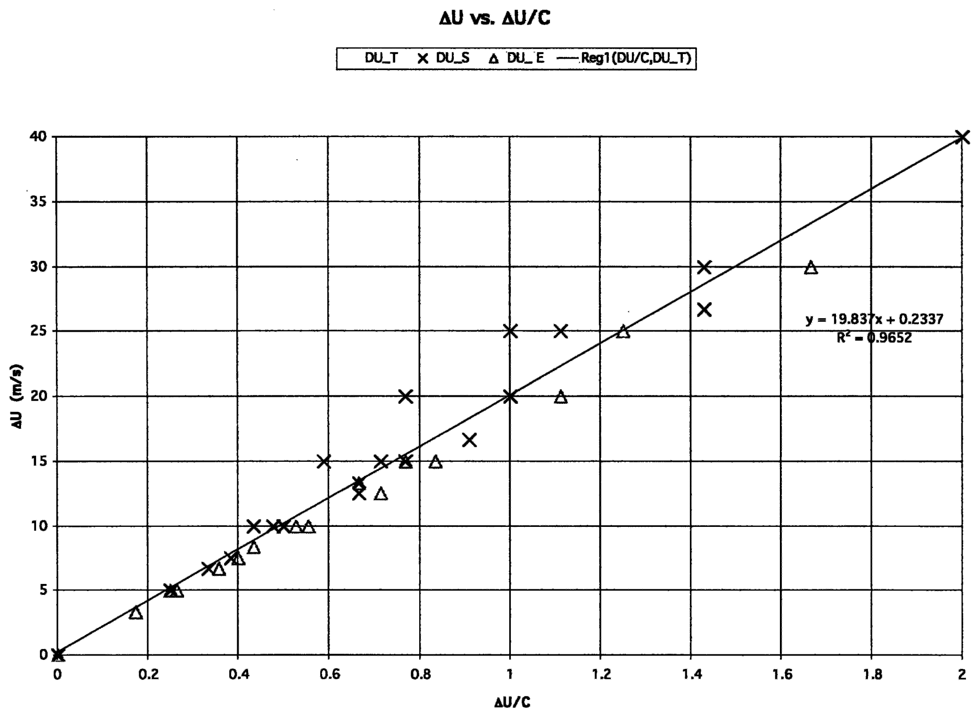

FIG. 5. Scatter diagram and linear regression line of ΔU on $\Delta U/C$. Crosses and triangles mark data points from simulations with surface-based and elevated shear layers, respectively.

them over their ranges. WR04 (p. 378) attribute these results to the development of "more isolated, three-dimensional cells or supercells (given convective initiation)," which "can mitigate the negative influence of stronger shears." Maximum vertical velocity and the average surface wind are weakly correlated with ΔU or $\Delta U/C$ (Table 1) and the peaks in the regression curves are broad and not located near $\Delta U/C = 1$ (Table 2). The average surface wind depends more on C than the other two independent variables. Maximum surface wind is the only quantity that is optimal near $\Delta U/C = 1$. However, it is also optimal at $\Delta U = 23.2$ m s^{-1}. The regression curves of maximum surface wind versus $\Delta U/$(20 m s^{-1}) and versus $\Delta U/C$ and the associated explained variations are nearly identical (Tables 1 and 2; Fig. 6).

We also computed regression curves for maximum surface wind versus $C/\Delta U$ to see if using $C/\Delta U$ instead of $\Delta U/C$ yielded higher explained variances. To accomplish this, we had to reduce the sample by 4 (the 4 no-shear cases for which $C/\Delta U = \infty$). We found that both the quadratic and the fourth-order regressions of maximum surface wind versus $C/\Delta U$ in fact had *lower* R^2 (0.2476 and 0.3194) than the R^2 (= 0.3659) for quadratic regression of maximum surface wind on $\Delta U/C$.

TABLE 1. Explained variations $R^2(x, y)$ according to quadratic single-regression analyses of the (left column) dependent variables y on the (top row) independent variables x. Entries in the second column indicate where the dependent variables are tabulated in WR04. The highest correlations in each row are in bold type.

	WR04's table	$x = \Delta U$	$x = \Delta U/C$	$x = C$
y = Total rainfall	2a	**0.864**	0.779	0.227
y = Condensation	2b	**0.545**	0.384	0.473
$y = w_{\max}$	2c	0.124	0.185	**0.213**
$y = u_{0\max}$	2d	0.359	**0.366**	0.120
$y = u_{0\text{avg}}$	2d	0.114	0.206	**0.458**

TABLE 2. Points on the quadratic single-regression curves of the (left column) dependent variables on the (top row) independent variables. Units for the dependent variables are m s^{-1}. The independent variables, $\Delta U/(20$ m s$^{-1})$ and $\Delta U/C$, are dimensionless and both range from 0 to 2. The points are given in (x, y) notation. The three points in each cell are at $x = 0$, at the peak of the curve, and at $x = 2$, in that order. These points determine the regression curve $y = ax^2 + bx + c$ for each case.

	$(\Delta U/20, y)$	$(\Delta U/C, y)$
$y = w_{\max}$	(0, 32.9), (1.77, 38.2), (2, 38.1)	(0, 32.2), (1.77, 38.7), (2, 38.6)
$y = u_{0\max}$	(0, 26.6), (1.16, 35.7), (2, 30.9)	(0, 26.5), (1.10, 36.1), (2, 29.4)
$y = u_{0\text{avg}}$	(0, 15.9), (0.63, 17.3), (2, 10.9)	(0, 16.3), (0.55, 17.4), (2, 9.2)

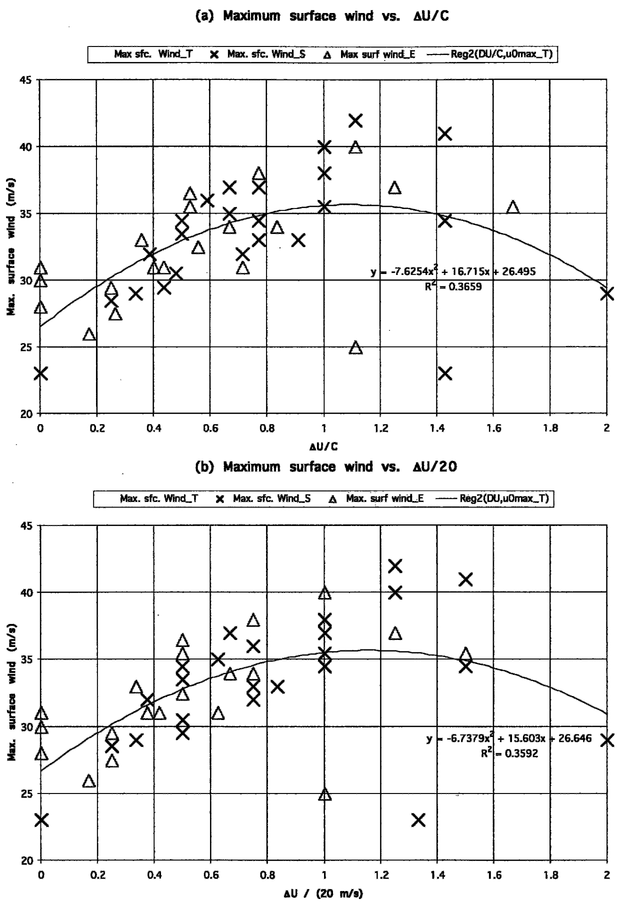

FIG. 6. Scatter diagrams and quadratic regression curves of maximum surface wind on (a) $\Delta U/C$ and (b) $\Delta U/(20\ \mathrm{m\ s^{-1}})$. Crosses and triangles denote the same as in Fig. 5.

These results indicate that the variations in C between 3 and 5 h as reported in WR04 are far too small to separate effects of ΔU from those of $\Delta U/C$. Therefore, the relative importance of the cold pool circulation to the system organization cannot be determined from the data in WR04. We hypothesize that the use of a single thermodynamic sounding in WR04 limits the variations in C in their model simulations, since Table 1b in WR04 indicates C only varies from 17.5 to 26 m s^{-1}, whereas the NCOMMAS runs presented herein show that C can reach 35 m s^{-1} (Fig. 3). A larger range of C should be found in any set of numerical simulations if these simulations are to apply to the range of observed squall-line behaviors.

4. Concluding remarks

We have shown that the hypothesized optimal state for squall lines as reconfirmed by WR04, in which the relative strength of the circulation associated with the storm-generated cold pool and the circulation associated with the environmental shear are nearly balanced, does not compare favorably with the available observations and even does not best explain the numerically simulated squall-line characteristics. We agree with WR04, and many others, that a certain amount of wind shear is very beneficial to squall lines. However, the most trustworthy way to examine a theory in the atmospheric sciences is to compare its predictions with observations and see how well it explains what is actually observed. These comparisons, while naturally imperfect due to errors in the observing systems, should be sufficient to either give credence to the theory presented in WR04 or to cause us to question its application to the atmosphere. Especially since WR04 (p. 382) state that the cold pool–shear relationships "represent the most fundamental internal control on squall-line structure and evolution" and (p. 381) "there is a strong degree of correspondence between the present cases that are more optimal from the $C/\Delta U$ perspective, and the tendency for the system to be composed of more erect, leading-line convection." We believe the observations presented herein lead one to question whether an appropriate balance is needed between the cold pool and ambient shear circulations for the enhancement of the strength and longevity of squall lines. The observational data suggest that, at best, the ratio of $C/\Delta U$ is not very useful in describing squall-line structure and that this concept should not be used to assist in the forecasting or nowcasting of squall lines. In addition, the environments of most long-lived squall lines have shear over deep layers and not just confined to the lowest 2.5–5 km as often assumed in WR04.

Finally, we wonder if the entire idea of an optimal state is not just a red herring that is more distracting than helpful. Admittedly, it is very challenging to refute an optimal state hypothesis with observations directly, since we cannot wind the clock backward in time, change the real atmosphere, and have the atmosphere rerun the case in question. We are left with examining the observational data we do have, and it is our contention that these data should show some hint of the hypothesized $C/\Delta U$ balance condition or we must question the veracity of this balance condition in the real atmosphere. Indeed, the question that operational forecasters have is not the academic question of whether or not the developing squall line is optimal, or even whether it could be stronger in some other environment, but the real-life question of whether the squall line will be severe or will sustain itself for another 300 km to threaten public safety in another part of the state or region. These are the questions that need serious attention, and the idea of optimality only appears to distract from the more important issues at hand.

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REFERENCES

Bluestein, H. B., and M. H. Jain, 1985: Formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during the spring. *J. Atmos. Sci.,* **42,** 1711–1732.

Coniglio, M. C., and D. J. Stensrud, 2001: Simulation of a progressive derecho using composite initial conditions. *Mon. Wea. Rev.,* **129,** 1593–1616.

——, ——, and M. B. Richman, 2004: An observational study of derecho-producing convective systems. *Wea. Forecasting,* **19,** 320–337.

Davies-Jones, R., 2002: Linear and nonlinear propagation of supercell storms. *J. Atmos. Sci.,* **59,** 3178–3205.

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

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 J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.,* **110,** 504–520.

——, and R. Rotunno, 2004: "A theory for strong long-lived squall lines" revisited. *J. Atmos. Sci.,* **61,** 361–382.

Wicker, L. J., and R. B. Wilhelmson, 1995: Simulation and analysis of tornado development and decay within a three-dimensional supercell thunderstorm. *J. Atmos. Sci.,* **52,** 2675–2703.