NOTES AND CORRESPONDENCE

Comments on "A Numerical Investigation of the Organization and Interaction of the Convective and Stratiform Regions of Tropical Squall Lines"

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The recent paper by Lafore and Moncrieff (1989; LM) deemphasizes the interaction of the low-level shear and the cold-air pool in regulating the intensity and longevity of squall lines. Although they recognize that "strong low-level shear and its interaction with the cold pool is important for maintaining cell development," they argue that "the generation of new cells is only part of the problem of sustaining a persistent mesoscale convective system" (LM, p. 542) and that one must consider vorticity generation throughout the system in order to evaluate the factors that influence system longevity. Their statements suggest an interpretation that stands in contrast to the proposal by Rotunno et al. (1988; RKW) that low-level shear, which counters the circulation induced by the cold thunderstorm outflow, is an "essential ingredient that sustains a long-lived line of time-dependent cells." In this Comment, we would like to respond to references made in LM regarding our paper (RKW), and to point out that their results appear to be compatible with our interpretation.

Before discussing specifics, we emphasize that as indicated by the title ('A theory for strong, long-lived squall lines'), RKW does not focus merely on system longevity; rather, it is concerned with interactions that promote strong convection over a long period, i.e. with overall system intensity (strength × longevity). We recognize that systems that do not achieve an appropriate balance between the low-level shear and the cold-pool strength may last a long time; however, we believe that in most instances, they will be weaker and shorter lived than if the shear were in balance with the cold pool. The root of LM's perceived discord between their ideas and our may stem from their focusing on somewhat differing system traits.

LaFore and Moncrieff observe, based on evidence provided in their Figs. 12b and 13b and from Dudhia et al. (1988), that the speed of the cold pool is different from the speed of the convective cells. From this they deduce:

> it follows that *the wind shear in the entire troposphere should be considered in the interaction of the cold pool and the convective cells.* This is in contrast to the theory espoused by RKW who maintain that the low-level shear is sufficient to ensure the longevity of squall lines.

(LM, p. 532, italics as in LM). To place this statement in proper perspective, we recall that Thorpe et al. (1982; TMM) determined from 2-D numerical simulations that the "low-level shear is a desirable and necessary feature" (TMM, p. 742) in prolonging the life of a squall line, and *they* proposed the idea of matching of the speed of the cold pool to the speed of the cells to explain the strength and longevity of the system. In RKW, we substantiate further the importance of low-level shear in influencing squall-line strength and longevity, and focus more specifically on the factors which determine the amount of shear that is most effective. However, our interpretation in RKW differs from TMM's concept of matching cold pool speed to cell speed. As stated in the Abstract of RKW: "Our analysis of this type of simulated squall line suggests that the interaction of a storm cell's cold surface outflow with the low-level shear produces much-deeper and less-inhibited lifting than is possible without the low-level shear, making it easier for new cells to form as old cells decay." The theory of RKW is not concerned with how the cells move relative to the system, but with whether they will be more or less intense as they form; this issue bears on *both* system intensity and longevity. We do not believe (and have never stated) that the "right amount" of low-level shear is "sufficient to ensure the longevity of squall lines;" rather, we regard it as an important factor in promoting this longevity.

In section 6 of LM a steady-state analysis of the vorticity field of the mature simulated squall line is presented. On p. 542 they state:

> The above analysis shows that a complete description of the vorticity field in squall-line type convective systems and its relation to system longevity is more complex than a local balance between the low-level inflow

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shear and the vorticity generated with the cold pool as hypothesized by RKW. *An important result is that it is an oversimplification to say that the interaction of the shear and the cold pool adequately explains the longevity of a mesoscale convective system because the organization of the vorticity fields is predominately on the scale of the entire system and not confined to a localized convection scale.*

In response to this statement, we emphasize that RKW does not purport to give a complete description of the vorticity field within a convective system—we only impress vorticity thinking into our service as a tool to explain why new cells find it easier form at the cold-air edge when there is low-level shear (see Fig. 18 of RKW.)

Although the diagnostic analysis of a steady state convective system as conducted in LM describes the balances maintaining that state, it cannot explain how the system evolved into that state, nor if conditions were to depart from those described by a particular steady-state balance, can it predict whether the system would begin to weaken or intensify further. The theory of RKW is an attempt to ascertain what is needed for a group of cells to evolve toward a vigorous long-lived system. Given a certain amount of instability and shear in a quiescent environment, RKW asks whether an initial disturbance will grow and interact with its environment to produce subsequent disturbances so that conditions approximating a steady-state system can be achieved. Viewed in this way, the steady analysis of LM and the developmental theory of RKW are complementary, rather than antagonistic.

The sensitivity experiments presented in LM also appear consistent with the interpretations presented in RKW. RKW suggested that the most favorable amount of shear for sustaining strong squall lines is related to a measure of the strength of the cold pool. If we denote the low-level shear by Δu and the strength of the cold pool by c, then one should expect the most favorable condition when $\Delta u/c \approx 1$ [cf. (10) of RKW]. Table 1 is constructed from the sensitivity experiments for the two COPT81 cases contained in Figs. 12–13 of LM; the maximum rainfall rate R_{max} is taken as an indicator of system intensity; the parameter C_* is roughly equal to the parameter c on the rhs of (8) in RKW and is a measure of the strength of the cold pool. The shear, Δu between the ground and 3.5 km (the typical height of the low-level jet maximum), is indicated for each experiment. One could say that all of the sensitivity experiments conducted by LM last a long time. However, the plot of all of the cases in Fig. 1 reveals a clear enhancement of the convective response as $\Delta u/c$ approaches unity, both for the strongly

TABLE 1. Results from the series of numerical simulations reported in LM. The last two columns (from Figs. 12c and 13c of LM) show the maximum rainfall rate, R_{max}, and the time it occurs, t_{max}. The strength of the cold pool, C_*, (from Figs. 12a and 13a of LM) varies with time so we compute a 4 h average centered at t_{max} (the starred times indicate that R_{max} occurred within 2 h of the end of the simulation, in which case C_* is the average for the last 2 h only.) Figure 2b of LM shows a variety of shear profiles; we tabulate here only the shear between the ground and 3.5 km, Δu, to highlight its importance in explaining the variance among the experiments with regard to rainfall rate which we take as a measure of system intensity.

Experiment	Δu (m s^{-1})	C_* (m s^{-1})	$\Delta u/C_*$	R_{max} (t m^{-1} s^{-1})	t_{max} (h)
23 June					
U	13	18.0	0.72	.18	9
X	16	19.0	0.84	.18	5
Y	20	20.5	0.98	.28	8
Z	24	21.5	1.12	.34	9
M	16	18.0	0.89	.22	*8
YL	20	21.0	0.95	.32	8
YI	20	21.0	0.95	.27	5
22 June					
M	16	8.0	2.00	.11	*8
ME	16	12.0	1.33	.20	*7
X	16	10.0	1.60	.16	6
XE	16	15.5	1.03	.23	5
XI	16	11.0	1.46	.22	6
G	16	14.0	1.14	.27	8

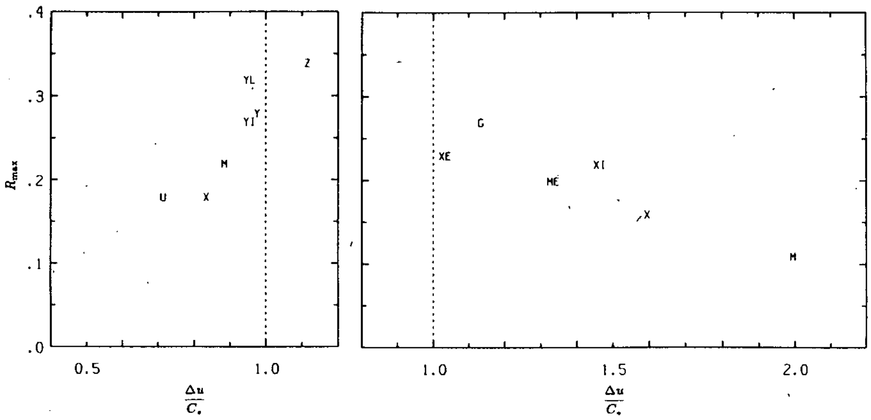

FIG. 1. R_{max} v. $\Delta u/C_*$ computed from the simulations of LM using the thermodynamic soundings from 23 June (left panel) and 22 June (right panel) COPT81 cases, respectively (see Table 1).

unstable (left panel) and the more weakly unstable (right panel) initial thermodynamic conditions. This behavior conforms precisely to our expectation!

LM state in their conclusions that:

> Although substantial low-level shear features in the COPT81 cases, *it is repudiated as a sufficient condition for their longevity because of the interaction between the convective and stratiform regions, for instance as evidenced by the system-scale vorticity generation.*

If an appropriate balance between the low-level shear and the cold pool is "only part of the problem," we believe it is a vital part, and is, in fact, a necessary (clearly not a sufficient) requirement for sustaining most strong squall lines. Their results appear consistent with our contention that this balance plays an important role in regulating the strength and longevity of squall lines.

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