Effect of Vertical Wind Shear on Numerically Simulated Multicell Storm Structure

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ABSTRACT

A strictly two-dimensional cloud model was used to gauge the effect of vertical wind shear on the mature phase behavior of model-simulated multicellular storms, extending the previous work of the authors. We specifically examined the propagation speed, quasi-equilibrium behavior, storm scale and updraft orientation of the model storms as a function of shear intensity. We also considered the precipitation efficiencies of our model storms and applied density current and Rotunno–Klemp–Weisman theories to our results.

Our previous work revealed that model storms could achieve a mature phase consisting of repetitive multicellular development when certain numerical obstacles were overcome. This was referred to as a "quasi-equilibrium state." We found herein that this state was also reached by model storms even when subjected to a very wide range of low-level wind shear intensities, although the temporal behavior during this stage was clearly dependent on the shear. We also found a very systematic relationship between the storm speed and the shear strength. Therefore, small shear values produced slowly moving storms which generally exhibited simple oscillations with time, fitting the classic multicell model. Larger shears resulted in complex oscillations similar to what has been termed "weak evolution," culminating in a nearly unicellular storm in the most extreme case.

The transition between the strongly and weakly evolving modes was abrupt in the wind shear spectrum, and the temporal behavior of the precipitation production was quite different between the two regimes. Yet, we also found that the precipitation efficiencies of these model storms were roughly constant among the simulations, irrespective of the low-level shear. The larger shear storms typically produced more precipitation, because they were processing water vapor at faster rates due to their more rapid propagation speeds, but were neither identifiably more nor less efficient in doing so. The rear inflow current feature, present in each case, appeared to play a major role in creating the colder subcloud cold pools which helped the storms formed in larger shear to move faster.

An important result is that none of the model storms suffered a terminal decaying phase, certainly not within a reasonable period of time. This suggests that the storm itself does not sow the seeds of its own demise, at least for the favorable, homogeneous environmental conditions considered and the simple, strictly two-dimensional framework adopted for this study.

1. Introduction

In Fovell and Ogura (1988, hereafter FO), attempts to simulate the structure of a midlatitude, multicellular squall line with a strictly two-dimensional (2D), non-hydrostatic cloud model were described. Initial conditions for the simulations were adapted from the environmental state existing prior to the 22 May 1976 Oklahoma storm which has been studied by Ogura and Liou (1980), and Smull and Houze (1985; 1987a,b). Simulations made with and without the incorporation of ice phase microphysics were presented.

The model storms described in FO were long-lived and evinced multicellular behavior during their mature phases. In each case, this phase followed a period of organization and was judged to have begun with the establishment of a system-relative upshear-tilting airflow. This airflow lifted air from the low-level environment ahead of the storm over the subcloud cold air pool, created by evaporative cooling, and expelled it out mainly towards the rear. Superimposed on this general airflow were individual convective elements, or cells, which were born at the leading edge of the storm and traveled rearward relative to that edge as they aged. These cells were found to have appeared in a remarkably periodic manner throughout the mature phase; FO called this a "quasi-equilibrium state."

Indeed, the attainment of the quasi-equilibrium state was one of the unique features of FO's simulations. In addition to being quite repetitive, this state also appeared to be essentially permanent (at least within a reasonable period of time). Part of the success was undoubtedly due to the adoption of favorable, but by no means atypical, initial environmental conditions. Also of major importance was the model design, which gave the storm a very wide and deep physical domain in which to develop and persist without being injured or otherwise unduly influenced by having artificial boundaries in close proximity. Fovell and Ogura reported that storms which organized in more restrictive...
horizontal domains were often found to either collapse into decaying stages (which resulted in the storm's demise) or experience extended, but rather irregular, mature phases, all depending on (and controlled by) the specific handling of the lateral boundary conditions.

The discussion in FO focused mainly on the behavior of the model storms while resident in the quasi-equilibrium mode. This was done because, while the early, temporary behavior of a model storm trying to organize could be affected by the specific procedure used to initiate the convection, the quasi-equilibrium state the storm ultimately achieved possessed a structure which appeared to be unique for the given environmental conditions. Once this state was established, the separation of the time-average of a variable from the deviations about it could be performed in an unambiguous manner since the transient portion representing the successive formation of individual convective cells proceeded in a remarkably periodic manner. This separation made it possible to reveal the broader features of the structure of a model storm through examination of the time-averaged fields.

While the quasi-equilibrium states achieved by the model storms described in FO were quite repetitive with respect to temporal behavior, they were not very simple. The storms were found to generate cells during the quasi-equilibrium stage in sets of two or three, depending on the experiment, and only the first cell of each set appeared to be truly independent from those which were generated previously. Independence between successive cells is a characteristic of the classic multicell storm model. The behavior of the other cells, which were termed "secondary cells," appeared to be more similar to what was referred to as "weak evolution" in Foote and Wade (1982) and Foote and Frank (1983). Those papers dealt with a case which possessed an updraft which was too unsteady for the storm to be considered a supercell or unicell, since it did consist of a series of cells, but at the same time the constituent cells were not clearly independent of one another as required by the classic multicell model. Periodic updraft surges began at the low levels over the gust front and advanced upward and rearward within the storm as in the classic model. The surges themselves, however, were but small perturbations on an established, persistent updraft. The term "weak evolution" was coined to distinguish this type of behavior from the classic multicell, or "strong evolution" model.

The present work represents an extension of FO in that we seek to investigate the effect of altering environmental wind shear on the model storm structure, with special attention on the quasi-equilibrium behavior. It has long been known from observations that wind shear is important in the organization, longevity and efficiency of convective storms (Newton and Newton 1959; Marwitz 1972a,b; Browning 1977). The studies of Takeda (1971) and Hane (1973) were among the first attempts to perform numerical investigations. Since then, numerous two- and three-dimensional modeling studies have been performed which have focused on the effect of wind shear, examining its intensity and/or its vertical distribution, including Thorpe et al. (1982), Weisman and Klemp (1982) and Droegemeier and Wilhelmson (1985), to name a few. Weisman and Klemp's (1982) results tended to confirm Moncrieff and Green's (1972) idea that convection is controlled by both buoyancy and shear. This can be summarized by using a Richardson number (Ri), a ratio between the convectively available potential energy (CAPE), which is the positive buoyant energy experienced by an air parcel rising from low levels, and the kinetic energy of the shear. Weisman and Klemp's results correlated well with observations which indicate that multicell storms develop in environments with large Ri while supercells are most commonly found in small Ri situations.

More recent work has included the studies of Dudhia et al. (1987), Nicholls et al. (1988), Lafore and Moncrieff (1989) and Weisman et al. (1988). The Dudhia study revealed that by manipulating the vertical wind profile of a tropical case, a multicellular model storm could be changed into a very interesting and unusual unicellular one. Both Nicholls et al. and Lafore and Moncrieff conducted large numbers of two-dimensional simulations to test the sensitivity of tropical squall lines to various environmental states, including vertical wind shear. Weisman et al., which used a three-dimensional model, concluded that for moderate shear intensities, two-dimensional models can capture the basic physics of squall line behavior.

The present study will differ from those cited above in that we wish to do detailed analyses of the influence of shear on the spatial structure and temporal evolution of the model storms. In particular, we will focus on the following points:

(i) Storm propagation speed. In the multicell model, storm propagation is usually thought of as a combination of continuous cell translation and a discrete component due to the establishment of new convection ahead of the older cells. In the model storms to be described herein, like those of FO, the new cell(s) in each repeat cycle in the mature phase appeared at the same position(s) within the storm relative to the gust front. Therefore, as in FO, the storm propagation speed is taken as that of the gust front, the leading edge of the cold subcloud outflow, as this is a persistent feature well known to be of fundamental importance in insuring the storm's survival. Several researchers have attempted to apply information gained from theoretical and laboratory models of density currents to atmospheric outflows with some success; recent examples include Miller and Betts (1977), Carbone (1982), and Wakimoto (1982). Rotunno et al. (1988) have advanced the idea that an "optimal state" exists when the positive (horizontal) vorticity of the low-level en-
environmental shear is in balance with the production of negative vorticity in the subcloud outflow.

(ii) Storm equilibrium behavior. In the ice-free case of FO the quasi-equilibrium state consisted of a 33 min cycle during which two cells were created. The first of the pair, the major cell, initially appeared as a new, discrete echo above the gust front, clearly separated from the older cells as in the classic multicell model. The other cell, the "secondary cell" of smaller relative intensity, made its first appearance farther behind the front as a perturbation on the previous major cell's updraft. This appeared to be most similar to the Foote and Frank "weak evolution" idea. Foote and Frank hypothesized that this weak evolution mode should fit into the Richardson number spectrum between multicells and supercells will be tested (within the limitations of the two-dimensional framework); the variation of shear given fixed buoyancy conditions will provide a spectrum of Richardson number conditions.

(iii) Storm scale, tilt and precipitation efficiency. While the model storms described in FO were long-lived they were not ever-expanding (at least with respect to the precipitating portion of the storm). Instead, in each case a different equilibrium width was reached. Fovell and Ogura attributed the ultimate width attained by a model storm to its ability to create precipitation particles in the cell updrafts and transport them rearward in the front-to-rear airflow, a trait which was sensitive to the model microphysics. The addition of ice to the model resulted in an expansion of the horizontal scale of the convective features but otherwise had little impact on the basic dynamics of the model storms. The scale expansion was due to the larger production and rearward spread of precipitation in the ice model storms, which allowed the features of the convective region to increase in scale by keeping the downdrafts moist over a wider region, essentially pushing the region marked by subsidence warming farther to the rear. Beneath this front-to-rear airflow in each model storm, a rear inflow current existed. This current was continuous throughout the storm, residing over the top of the subcloud cold pool where it was shallow in the subcloud region, and crossing into the cold pool as the pool became deep near the leading edge. Such inflow currents have been observed in both midlatitude and tropical squall lines (e.g., Smull and Houze 1987b; Chong et al. 1987; Houze and Hobbs 1982) and have been successfully simulated (for example, by FO as well as Lefore and Moncrieff 1989). FO noted (and Fovell, 1988, demonstrated; see in his Fig. 3.13) that in their model storms, the rear inflow current became established near the leading edge of the convection early in the course of the simulation, a consequence of horizontal pressure gradients, and spread rearward with time, eventually reaching an equilibrium orientation and intensity along with the rest of the storm. They speculated that this current may have influenced their model storms since it transported warm, dry air from the subsidence region into the cold pool, and also may have been exaggerated in intensity by mass continuity constraints, which are particularly severe in a 2D model. These hypothesis will be considered and related to questions concerning circulation tilt and precipitation production.

2. Model

The model used in this study is the same as that used in FO, with some exceptions to be noted. Briefly, the model is strictly two-dimensional and uses the anelastic equations. A vertically stretched grid is employed to increase resolution at the lowest levels; the finest grid interval there is 200 m and the model top resides at approximately 22 km. The horizontal grid is stretched outside of a central high resolution (1 km) zone where the strongest portions of the storm will reside. In FO, the width of this fine grid region was taken to be either 115 or 315 km, depending on the experiment; here, all of the simulations have been repeated twice, using both widths. Fovell and Ogura took their stretched grid region on each side to be 70 grid points wide and employed a stretching rate of 1.075:1; this resulted in a physical domain that was about 4500 km wide. For this study, we have also rerun the more important cases using a (numerically) wider, even more gently stretched grid zone that yielded the same physical domain width; the results of these runs will be noted where appropriate.

Sensitivity test conducted in the manner as those reported by FO indicated that the differences between the small and large fine grid region runs for these simulations were not serious in substance, although they could and sometimes did slightly affect the regularity of the surface precipitation patterns produced by the storm by introducing small amplitude oscillations into the results that had periods much longer than the fundamental cell development cycles. Of far greater importance was the handling of the lateral boundary conditions. As already noted in the Introduction, FO reported that simulations made with small physical domains (which amplify the importance of the boundary conditions) often resulted in the production of storms which entered a pronounced decaying phase after (or in place of) a short-lived mature state. Since these decaying phases either disappeared or were substantially delayed in onset when the domain was enlarged, we did and still do consider them to have been spuriously forced.

The vertical temperature and moisture profiles and initialization technique employed by FO are used again here. The sounding is quite unstable, possessing a large amount of CAPE (~2500 J kg\(^{-1}\)) as is typical of Oklahoma springtime convection (Bluestein and Jain 1985). The initial forcing was provided by a symmetric bubble of warm, humid air placed in the low-level environment. All of the simulations reported on herein
were made without implementing ice microphysics and therefore the only forms of condensed water allowed were cloud droplets and rain water.

3. Experimental design

The wind shear profiles used in the following simulations are depicted in Fig. 1. For the present, we are restricting ourselves to examining linear, unidirectional wind profiles with shear confined to below 2.5 km, the kind of conditions investigated by Rotunno et al. (1988) and Weisman et al. (1988). Experiments will be designated by $\Delta u = n$, where $n$ is the difference between the wind speed at 2.5 km and the surface in meters per second. Ground-relative surface winds were taken to be zero. This differs from FO where the ground-relative wind speed was 5 m s$^{-1}$ from the east and should be kept in mind when interpreting the model storm propagation speeds reported in this paper.

A series of experiments were conducted with $\Delta u$ varying between 5 to 30 m s$^{-1}$. Bulk Richardson numbers, computed in the manner of Weisman and Klemp (1982), ranged from 15 for the $\Delta u = 30$ profile to 521 for the weakest shear case (see Table 1). This includes the range of Richardson numbers usually attributed to multicell storms. Difficulties exist, however, in producing or interpreting model storms in environments at the extreme ends of this wind shear spectrum. For example, this grid arrangement is inappropriate for the examination of convection in extremely low shear environments ($\Delta u < 5$) as those tended to support two separate storms which propagated in opposing directions. This situation is most obvious in a shearless case in which two mirror-image storms would necessarily be created from a symmetrical initial forcing. In order to keep a model storm within the fine grid region during the course of the simulation, the grid is translated; under conditions of extremely small vertical shear, the tracking of one of the storms would force the other to enter the stretched grid region where it would be dissipated in an unrealistic manner.

The constraints of the model’s geometry may not be overly restrictive for the smaller shear cases but certainly a storm developing in a highly sheared environment will find the model’s two-dimensionality extremely confining. In nature, wind profiles with very large low-level shear intensities tend to produce splitting storms with three-dimensional, rotating updrafts; this has also been found to be true in various numerical experiments (e.g., Weisman et al. 1988). In addition, the amount of time required for a model storm to settle down into a mature state marked by quasi-equilibrium behavior increased greatly with the shear; other modelers have found high shear cases to possess protracted organizing stages. Some of the simulations were carried out as long as 19 h, and these very long integrations underscore the limitations of the model framework. Because it is strictly two-dimensional with time-independent and horizontally homogeneous environmental base state conditions, the framework neglects processes that would be active over long time scales such as Coriolis accelerations and diurnal as well as spatial variabilities. Still, these experiments are useful as demonstrations of model storm behavior under highly idealized (if overly restrictive) conditions and, in any case, the examination of the behavior of the model in general under extreme conditions will be shown to be of interest in itself.

4. Results

In this section, we will describe various aspects of the behavior of these model storms, focusing almost exclusively on the stage in their evolution which we have referred to as the mature phase, the stage of storm evolution marked by the essentially periodic production of new cells. This state was achieved by each of

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**Table 1. Some numerical statistics.**

<table>
<thead>
<tr>
<th>$\Delta u$ (m s$^{-1}$/2.5 km)</th>
<th>$\frac{\gamma}{g}$ number (RI)</th>
<th>$\frac{G}{(m s^{-1})}$</th>
<th>$\frac{\Delta p}{(mb)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>521</td>
<td>11.4</td>
<td>1.14</td>
</tr>
<tr>
<td>7.5</td>
<td>232</td>
<td>14.8</td>
<td>1.67</td>
</tr>
<tr>
<td>10.0</td>
<td>131</td>
<td>15.6</td>
<td>1.89</td>
</tr>
<tr>
<td>12.5</td>
<td>84</td>
<td>17.3</td>
<td>2.04</td>
</tr>
<tr>
<td>15.0</td>
<td>58</td>
<td>19.0</td>
<td>2.25</td>
</tr>
<tr>
<td>17.5</td>
<td>43</td>
<td>20.7</td>
<td>2.42</td>
</tr>
<tr>
<td>20.0</td>
<td>33</td>
<td>22.8</td>
<td>3.25</td>
</tr>
<tr>
<td>22.5</td>
<td>26</td>
<td>24.8</td>
<td>3.68</td>
</tr>
<tr>
<td>(25.0)</td>
<td>21</td>
<td>26.5</td>
<td>3.75</td>
</tr>
<tr>
<td>(27.5)</td>
<td>17</td>
<td>28.3</td>
<td>4.11</td>
</tr>
<tr>
<td>(30.0)</td>
<td>15</td>
<td>30.1</td>
<td>4.34</td>
</tr>
</tbody>
</table>

**Fig. 1.** Vertical wind profiles used in the experiments. In each case, the shear was linear over the lowest 2.5 km, with zero shear above.
the model storms we created. For reasons which will be explained below, this last statement applies most rigorously to the storm that issued from environments with moderate shear intensities. The extreme cases, however, do not detract from the important result that none of the model storms convincingly exhibited a decaying phase following its mature phase, despite model integrations which were often very long.

a. Propagation speed

Storm propagation speeds relative to the ground achieved by the various model storms during their mature phases are listed on Table 1 and are also depicted graphically against the shear in Fig. 2. In every case, once the model storm finished organizing, its cold subcloud outflow developed an essentially unvarying propagation speed which remained constant over even short time periods, and this occurred despite the fact that the airflow within the body of the outflow itself was strongly time-dependent. The striking result of these data is the very nearly linear relationship between the storm propagation speed \( G \) and the low-level shear over much of the wind shear range. Neglecting for the moment the \( \Delta u < 10 \) cases, the equation of the linear relationship is

\[
\hat{G} = 8.11 + 0.734\Delta u \quad (\Delta u \geq 10). \tag{1}
\]

In (1), \( \hat{G} \) is the estimate of the true propagation speed \( G \), differing from it by the error or residual term \( \epsilon \) (i.e., \( G = \hat{G} + \epsilon \)). The coefficient of determination (or \( R^2 \), indicating the fraction of the variance explained by the model) for this line is 0.9993. On Table 1, the values of wind shear enclosed in parentheses (\( \Delta u > 22.5 \)) represent model storms that were initialized using the \( \Delta u = 22.5 \) run at 14 h, a time at which the storm was well into its mature phase. In those runs, the wind shear was allowed to increase gradually at a rate of 2.5 m s\(^{-1}\) h\(^{-1}\). This was done since simulations with these very large shear environments produced model storms that failed to survive the initial organization period. We will deal with the subject of these very highly sheared cases later.

Inspection of Fig. 2 shows that all of the values of these basic experiments, indicated on the figure by squares, fall along a line with the exception of the \( \Delta u = 7.5 \) case. Sensitivity tests performed on this case failed to reveal any flaws in the simulation. In fact, the results of further tests, conducted using wind shear intensities in the neighborhood of this case, demonstrated that the deviation from the apparent linearity around \( \Delta u = 7.5 \) is not an artificial result. Instead, there is a suggestion that these wind shear experiments can be divided into two or perhaps even three separate regimes.

Due to the simplicity of the input wind profiles, the average system-relative wind speed in the 2.5 km shear layer for each case can be taken to be the quantity \( (0.5\Delta u - G) \). Above the shear layer, the midlevel system-relative average wind speed can be estimated as \( (\Delta u - G) \). These estimates are valid for the undisturbed (prestorm) environment and also the remote environment far ahead of the storm at any time during the simulation, although they ignore the variation of density with height. In Fig. 3a, the low-level storm-relative inflow is plotted against the midlevel relative inflow. It can be seen that, in general, the lowest shear cases (\( \Delta u < 7.5 \)) had relatively weak inflow in the shear layer which was not much stronger than the inflow aloft. Midlevel inflow was strongest for the \( \Delta u = 7.5 \) case and the storms achieved propagation speeds that led to making the average low-level inflow nearly constant through the range from \( \Delta u = 7.5-10 \). Above \( \Delta u = 10 \), the low-level inflow strengthened while the midlevel headwind diminished in intensity from case to case. The figure suggests that the cases basically fell into three groups with respect to the system-relative airflow.

On the other hand, Fig. 3b portrays the midlevel inflow plotted against the ratio between the midlevel and low-level average winds. The ratio was chosen because it is thought that the relative intensities of the two are more revealing than either estimate is separately. This plot suggests that two groups existed, with the lowest shear cases (5 \( \leq \Delta u \leq 7 \)) differing from the others. Among the higher shear cases, there was a consistent decrease in the midlevel headwind, both in absolute terms and relative to the low-level inflow, as the shear was increased.

It can be noted that in every case \( \Delta u < G \), which implies that, at least with respect to the prestorm environment, none of these storms had a "steering level" where the system-relative horizontal wind was zero. Instead, these storms experienced relative inflow

![Fig. 2. Mature phase gust front propagation speeds plotted against the 2.5 km vertical wind shear. Squares denote data points for the experiments listed on Table 1; diamonds represent results of additional sensitivity tests not described in the table.](image-url)
difference between $\Delta u$ and $G$ generally decreased; by
the largest shear case, $\Delta u = 30$, the difference was es-
sentially zero. We will use this observation later.

Despite the complication introduced in the smallest
shear cases, it can be said that these model storms be-
haved in a very systematic manner across the range of
wind shear values considered here. We can make the
observation that the more strongly sheared storms de-
veloped deeper and colder subcloud cold pools; it is
known from the theoretical and laboratory studies of
density currents that both of these factors translate into
faster propagation speeds. This tendency can be seen
in Fig. 4, which depicts fields of perturbation potential
temperature (with respect to the initial state), averaged
through time in system-relative manners, for the $\Delta u$
$= 5$, 12.5, 20 and 22.5 cases. These cases were chosen
as representative of model storms in the small, medium,
large and very large wind shear environments. In this
figure, the horizontal axes represent 90 km sections of
the 315 km central fine grid, oriented in each case so
that the surface gust front is positioned at about $x$
$= 70$. The vertical axes represent height, with tick
marks spaced 450 m apart; only the tropospheric por-
tion of the domain is shown. The time-averaging tech-
nique, which was also used by FO, helps reveal the
broader features of the fields by smoothing out the
transient, smaller-scale variations. The time interval
used in the averaging process was different in each panel
in the figure, having been chosen to correspond to an
integral number of mature phase repeat cycles. The
nature and length of the repeat cycles will be given in
the next subsection.

A difficulty in relating the propagation speed of the
model storm to density current theory lies in the wide
variety of relationships that have been developed. The
various techniques employ different variables and
characteristic depths, and thereby result in different
Froude numbers. In theory, the Froude number is the
ratio between the inertial and gravity forces, but in
practice is a proportionality factor between $G$ and a
"densimetric" speed $U^*$ affected by many processes
such as friction. The reader is referred to Droegemeier
and Wilhelmson (1987, hereafter DW) for a summary
of some of these various relationships. In addition, these
relationships do not explicitly handle the effects of mo-
momentum transfer from periodically developing dow-
drafts to the horizontal flow within the subcloud out-
flow, but this effect was apparently dominated by other
factors since in each of our model storms, the leading
ege of the outflow achieved a very nearly constant
propagation speed with time in the mature phase.
Time-dependent fluctuations in the airflow within the
body of the density current were far larger than the
variations in the rate of movement of the outflow-en-
vironment interface.

One approach appeals directly to hydrostatics as the
explanation for the motive force driving a density cur-
current. We have sought a relationship between the prop-
agitation speed and the difference in the time-averaged surface perturbation buoyancy pressure \((p_b^*)\) across the gust front. Buoyancy pressure is that subdivision of the total perturbation pressure field which excludes effects directly related to the velocity field (dynamic pressure, \(p_d^*)\) but incorporates within it what is usually termed hydrostatic pressure (see FO; Williamson and Ogura 1972). The advantage of this relationship is that it does not depend on just one point or one vertical section in the cold pool. Also, it implicitly includes the effect of the warm cloud over the outflow as well as the variation of the density surplus with height within the outflow, both of which are usually absent or neglected in laboratory-derived relationships. As in FO, the time-averaged pressure fields were derived from averaged temperature, moisture and velocity fields.

In these model storms, the surface buoyancy pressure was typically at a maximum beneath the outflow "head," where the depth of the cold pool is greatest, and possessed a local minimum at a point just ahead
of the gust front, within 1 or 2 km of the temperature break. This pressure anomaly was opposed by a local maximum in the other partial pressure, dynamic pressure, which was highest at the gust front where the cold outflow and warm environmental air collided, and lowest further behind where the horizontal flow was accelerated towards the front. In the smaller shear cases, the outflow head was not sharply defined (Fig. 4) and the $p_b^*$ maximum resided far behind the leading edge. In these cases, the distribution of total pressure along the surface displayed two distinct local maxima, one dominated by $p_b^*$ and the other by $p_a^*$. This was obscured in the more highly sheared cases where the head was well defined but the maxima of each partial pressure were not well separated. For this reason, we have elected to focus on buoyancy pressure rather than on the total.

In the small $\Delta u$ storms, however, the variation of time-averaged $p_b^*$ along the surface between the maximum and the gust front was not very regular and a simple difference between the extremes on each side did not provide an accurate representation of the true difference in this pressure across the front. This can be seen in Fig. 5, which plots $p_b^*$ against distance from the gust front, from the absolute maximum value behind the front to the local minimum value ahead, for the basic experiments. In each case, the plotted values have been normalized by subtracting the minimum value.

Therefore, we elected to calculate $\Delta p_b^*$ as the spatially averaged difference across the gust front; these values are listed on Table 1. The clear relationship between $G$ and $\Delta p_b^*$ which can be detected on the table can be improved with a transformation on $\Delta p_b^*$, and an equation of the form

$$G = k(\Delta p_b^*/\rho)^{1/2} = kU^*$$

(where again $G = \hat{G} + \epsilon$ provides a good fit ($R^2 = 0.995$) to the data when $k$ is 1.27. Here, $k$ is the Froude number, $U^*$ is the densimetric speed defined earlier and $\rho$ is the density of the undisturbed air in the environment averaged over the depth of the outflow head, which ranged from 0.99 to 0.94 kg m$^{-3}$ among the cases.

The relationship in (2) is reasonable in terms of hydostatics but the fit, while good, is defective in the sense that $\epsilon$, the error in the estimation of $G$, is a systematic function of $G$ itself—such as $\Delta u$ as well, due to (1)—indicating a missing term in the relationship. Droegemeier and Wilhelmson found $k$ to be constant among their numerical experiments, irrespective of the method of calculation, but all of their simulations were made using a calm initial environment. Simpson and Britter (1980) examined the results of laboratory experiments and atmospheric data and deduced that the ambient environmental flow influences the propagation speed of a density current or storm. The speed was found to be larger than expected from theory when the ground-relative mean flow ($U_2$) was in the same direction as the current was moving. Taking in our case a simple estimate of $U_2$ to be the mean ground-relative wind speed within the shear layer (i.e., $0.5 \Delta u$), the following equation

$$\hat{G} = k(\Delta p_b^*/\rho)^{1/2} + \lambda U_2 = kU^* + \lambda U_2$$

was tested on the data and resulted in an improved fit ($R^2 = 0.9997$) with better error behavior when $k = 0.89$ and $\lambda = 0.70$.

The values of $k$ and $\lambda$ obtained here are comparable to Simpson and Britter's estimates (0.87 and 0.59, respectively). This, however, may simply be coincidental since they calculated $U^*$ in a different manner, using the depth of the shallower following flow (or body) behind the head along with the density surplus. We believe that averaging the pressure along the surface beneath the head was appropriate in our case since, unlike the situation in two-fluid laboratory currents, the density surplus within the model storm outflow varied with distance from the front and decreased with distance in the following flow. This created ambiguities which were perhaps not present in the laboratory tank experiments. Both approaches may actually be describing the same physical process, however, since in our model storms the depth of, and cooling within, the following flow is correlated with the same characteristics in the head region. The correction term ($U_2$) in our application essentially compensated for the fact that as the shear was increased, the buoyancy pressure difference across the gust front became more concentrated, making the spatially averaged difference less representative of the true situation. This can be seen in Fig. 5.

![Fig. 5. Time-averaged surface buoyancy pressure distribution (mb) across the gust front for the model storms. Plotted values have been normalized by subtracting the local minimum value which was located at either 1 or 2 km ahead of the time-averaged gust front position.](image)
b. Storm equilibrium behavior

In FO, model storms which periodically underwent multicellular redevelopment were presented. In both the ice-free and full ice model cases, the oscillation was complex, consisting of major and secondary cells as described in the Introduction. In this section, we focus on the effect of wind shear on the form and substance of the rather periodic or quasi-equilibrium behavior that comprised the mature phase.

Figure 6 presents time histories of domain maximum vertical velocity (m s\(^{-1}\)) and subcloud minimum buoyancy for two cases, \(\Delta u = 7.5\) and 20, for the 15 h period these simulations were integrated. The maximum updraft histories are similar between the two cases in that they were both able to settle into reasonably repetitive mature states following initial periods of organization. The initial phase for the \(\Delta u = 7.5\) storm (Fig. 6a) was rather short and the mature phase consisted of rapid oscillations representing new cell generation within the storm system on a rather short time scale. The oscillations continued for as long as the sim-
ulation was conducted and the slight tendency for the maximum updraft attained by each successive cell to be less intense over the last 5 h of the experiment does not appear to represent an incipient decaying phase in the system. This minor decline, in fact, was substantially eliminated from the otherwise virtually identical results which were obtained in a simulation that used the numerically wider, more gentle stretched grid zone described earlier. The \( \Delta u = 20 \) wind profile (Fig. 6b), on the other hand, induced a storm which had to undergo an extended organizing stage that abruptly concluded at about 450 min into the simulation and ultimately resulted in the establishment of a more powerful system. In this case, employment of the more gently stretched model design in this larger shear case resulted in greater differences, but these will not affect the discussion or conclusions presented below. The histories of the subcloud minimum buoyancy (Fig. 6c), a measure of the strength of the cold pool used by Rotunno et al. (1988) and FO, also demonstrate that the weaker shear simulation more rapidly settled into a less intense (and, by density current theory, a more slowly moving) storm system.

Diagrams such as those presented in Fig. 6 are popular in the modeling literature but can be deceptive due to their reliance on but a single point in the domain at any one time, and this limitation is especially crucial as they also usually provide no information as to the whereabouts of the points in question. Very useful supplementary information is contained in diagrams such as those presented in Figs. 7 and 8, which show the time history of system-relative precipitation intensities (mm h\(^{-1}\)) produced by these two model storms, respectively, over periods of approximately two hours during their mature phases. The horizontal axes are again oriented so that the gust front resides over \( x = 70 \). The vertical axes are time, increasing upwards; individual ticks are separated by 2 minutes.

The \( \Delta u = 7.5 \) storm achieved what can be considered as a simple oscillation with time, something which was already suggested in Fig. 6a. Individual precipitation bursts, with very nearly the same pattern and maximum intensity, were separated by 16 min. The diagram very clearly shows that the mature phase's quasi-equilibrium oscillations in storm intensity consisted of the successive generation of new cells which then moved rearward with respect to the storm rather than the periodic reintensification of but a single cell, and therefore the model storm qualified as multicellular. The \( \Delta u = 20 \) storm oscillation was also multicellular but more complex, with a fundamental repeat cycle of about 42 min. In both cases, the start of a major precipitation burst was associated with the development of a major cell which had formed over the gust front as a new, relatively discrete updraft center within the sweep of the front-to-rear airflow rising over the front. The \( \Delta u = 7.5 \) storm proceeded without developing intermediate secondary or minor cells, whereas the larger shear case possessed two such cells between each major cell. The second minor cell in each of the \( \Delta u = 20 \) storm's repeat cycles was extremely weak and barely perceptible in the rainfall diagram although it could be detected in the vertical velocity cross sections (not shown).

The evolution of echoes in these two model storms can be seen in Figs. 9 and 10 which depict the time history of column maximum radar reflectivity for the same time periods as Figs. 7 and 8. Radar reflectivity, a function of rainwater content alone in these ice-free simulations, was computed using the method described in FO. In computing the column maxima, echoes which existed beneath the 2.5 km height level were not considered. This was done so that reflectivity associated with rainwater brought forward to the gust front in the subcloud airflow would not obscure the appearance of developing "first echoes" (the discrete radar signature of the major cells), which in all cases became established at higher levels.

It can be seen in these figures that the \( \Delta u = 7.5 \) oscillation was indeed simple and that of the \( \Delta u = 20 \) case was complex. In the former case, the appearance of a new cell coincided with the establishment of a new, discrete echo above \( x = 68, 2 \) km behind the surface gust front location. Figure 11a, which depicts fields of reflectivity and cloud water at the time of a first echo appearance, emphasizes the discreteness of this feature, which is exaggerated since ice was not included and cloud water was assumed to be nonreflective. Figure 9 shows that each independent echo subsequently exhibited a full life cycle of intensification and decay as it traveled rearward relative to the storm and reached maximum intensity at about 15 km behind the gust front.

New echoes were less well differentiated from the preexisting echo mass in the \( \Delta u = 20 \) case (Fig. 11b). Also, precipitation was considerably heavier, each burst longer lasting, and concentrated much closer to the leading edge. One might compare the rainfall intensity and maximum reflectivity plots and note that the points of maximum reflectivity and greatest surface rainfall for a given cell do not overlap in time and space. This is because a plotted reflectivity value represents a midlevel maximum combined with the fact that the cells tended to lean rearward with height as they aged.

Among the small shear cases, the \( \Delta u = 7.5 \) storm developed the simplest, most regular rainfall oscillation, and this is why this case was chosen for closer analysis. Simulations with even smaller shears did not generally settle into mature phases which were as strictly periodic and stable with time. Instead, in these simulations, some random differences existed among the mature phase cell redevelopment cycles which could neither be attributed to longer period oscillations nor be eliminated in sensitivity tests. The bulk Richardson numbers associated with these cases are quite large (>240) and indeed observations indicate such values are usually associated with more disorganized multicellular
\( \Delta u = 20 \)

Column maximum reflectivity (dBZ)

\( x \) (km)

\( (\mu) I \)

Fig. 10. Column maximum radar reflectivity for \( \Delta u = 20 \) case. Time period shown same as in Fig. 7. See caption of Fig. 9 for more details.

\( \Delta u = 7.5 \)

Column maximum reflectivity (dBZ)

\( x \) (km)

\( (\mu) I \)

Fig. 9. As in Fig. 7 but for column maximum radar reflectivity for \( \Delta u = 7.5 \) shown. Computational method is described in the main caption for Fig. 6 at 1 dBZ.
convection (Weisman and Klemp 1982). It is possible that the failure to achieve such strict periodicity is a characteristic of the separate regime to which Figs. 3a and 3b suggested those cases belonged. It has already been suggested by Figs. 4 and 5, however, that the inflow updrafts of these cases were horizontally very drawn out; this probably enhanced the opportunity for random (nonlinear) effects to make an impact on the cell development cycles. Other than the presence of greater randomness in these very low shear simulations, however, the essential dynamical structures of these storms were little different from those which did settle into more clearly obvious quasi-equilibrium states (Δu ≥ 7.5). One of the most important of the similarities is that none of the storms evinced definite decaying phases for as long as the simulations were carried out.

The transition from the simple oscillation of the Δu = 7.5 case to the complex cycle of the Δu = 20 storm occurred gradually as the shear was increased. Table 2 presents information about the behavior of the cellular development cycles for the basic experiments, listing the length of the repeat cycle (or, equivalently, the period between first echoes or major cell developments), the number of secondary cells which appeared in each cycle and the average period between cells, whether major or secondary. The tendency for the model storms to develop secondary cells began with the Δu = 10 case; Fig. 12 presents the rainfall diagram for the mature phase of this storm. While this case did possess the same 16 min average period between cells as the Δu = 7.5 simulation, alternate developments in the larger shear case has less intense updrafts, produced weaker rainfall bursts and were established farther behind the leading edge than the other cells. The rainfall diagram clearly shows that the cells tended to appear in sets of two. The later appearing cell of each set was designated as possibly secondary for the purposes of Table 2 primarily due to its relatively smaller intensity, although in this case the cell retained some of the characteristics we have come to associate with major developments as a result of examining these simulations.

One of these characteristics is the ingestion of air of low equivalent potential temperature (θ_e) from the

<table>
<thead>
<tr>
<th>Low-level shear (Δu) (m s⁻¹/2.5 km)</th>
<th>Time between first echoes (min)</th>
<th>Secondary cells per cycle</th>
<th>Average period between cells (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>~12</td>
<td>0</td>
<td>~12</td>
</tr>
<tr>
<td>7.5</td>
<td>16</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>10.0</td>
<td>32 or 16</td>
<td>1 or 0</td>
<td>16</td>
</tr>
<tr>
<td>12.5</td>
<td>36</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>15.0</td>
<td>40</td>
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<td>20</td>
</tr>
<tr>
<td>17.5</td>
<td>40</td>
<td>1</td>
<td>20</td>
</tr>
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<td>20.0</td>
<td>43</td>
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<tr>
<td>22.5</td>
<td>∞</td>
<td>(all)</td>
<td>17</td>
</tr>
<tr>
<td>(25.0)</td>
<td>∞</td>
<td>(all)</td>
<td>17</td>
</tr>
<tr>
<td>(27.5)</td>
<td>∞</td>
<td>(all)</td>
<td>17</td>
</tr>
<tr>
<td>(30.0)</td>
<td>∞</td>
<td>(all)</td>
<td>15</td>
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midlevel environment on the forward side which occurs during the creation of each major cell in the mature phase. FO described this event to point out that a substantial fraction of the low $\theta_e$ air that made up the subcloud cold pool did come from the front side of the storm during the upshear-tilting mature phase, despite the two-dimensionality of the simulation. Low $\theta_e$ air is always present at midlevels ($z \sim 4.5$ km) ahead of each of the model storms but, although it has already been shown that system-relative inflow was present there in every experiment, the updraft in each case acted as a barrier to the airflow there, preventing the air at those levels from entering the storm. The developing major cell altered the storm's airflow drastically enough, however, to force a pocket of low $\theta_e$ air from the midlevel environment to be pinched off and drawn into the body of the storm. Some of this low $\theta_e$ air was mixed into the updraft of the previously existing cell, lowering the equivalent potential temperature of its air. The rapid decay of the older cell which ensued allowed the rainwater trapped within it to fall out, helping to establish an intense low-level downdraft in the rain shaft beneath it (See FO's Fig. 9). Note that while Rotunno et al. (1988) also discussed the induction of forward side $\theta_e$ into a model storm, they only demonstrated that the process occurred during what we have referred to as the organizing phase of the storm's existence.

This ingestion of low $\theta_e$ air did not occur during the development of cells which were truly secondary in nature since their creation did not involve a sufficiently drastic alteration in the storm's updraft orientation. Instead, these cells were formed within the updraft of the previously existing cell. Using this criterion, the alternate cells in, for example, the $\Delta u = 12.5$ case were clearly secondary, although those of the $\Delta u = 10$ case were not. An interesting pattern emerged from these simulations in that the cells which did not ingest the potentially cold air were substantially slower in their decay and developed much weaker downdrafts beneath them than those which did ingest it.

Table 2 shows that as the low-level shear was further increased, so did the time interval between successive major cells and the number of secondary cells appearing in-between. Note that while the repeat cycle continued to lengthen, the average period between successive cellular developments, whether major or secondary, remained in the range from 12–22 min. These average statistics are slightly misleading in the sense that they implicitly contain the assumption that all of the cells were equally spaced in time within each repeat cycle and this was not strictly true; however, they do serve to suggest the existence of a fundamental oscillation, common to all the model storms, which was increasingly masked or modulated as the shear was increased. More will be said about this in later sections.

The increase in the production of secondary cells, which came at the expense of major developments, culminated in the $\Delta u = 22.5$ case. This case, the strongest wind shear simulation to survive the initialization phase, looked something like the $\Delta u = 20$ storm (but with considerably less coherence among the cell intensification cycles) until about 11 hours, the time after which it finally settled down and displayed a temporal structure which no longer varied much with time. This storm's mature state differed from that of the $\Delta u = 20$ case in a number of interesting ways, all of which survived sensitivity testing. All of the cells which appeared during this somewhat delayed mature phase were deemed to be secondary in nature. Figures 13 and 14, which present rainfall intensity and maximum reflectivity diagrams for this storm, show that the small increase in shear over that in the $\Delta u = 20$ case has eventually resulted in a decidedly different precipitation pattern. It can be seen that while this storm produced periodic bursts of rainfall, each burst was of relatively small magnitude compared to those in the $\Delta u = 20$ case (Fig. 8). In addition, the increase in the rainfall intensity in each burst above what could be considered the background rate was rather small. This behavior was quite different than what was found in the smaller shear cases which possessed a distinct rainfall minimum at the conclusion of each repeat cycle, a minimum that helped to identify the cycle in the rainfall diagrams.

Also unlike the previously examined simulations, the maximum reflectivity structure through time near the leading edge where the secondary cells were established revealed no significant temporal oscillation; the amplitude in Fig. 14 was less than the contour interval of 6 dBZ. In fact, Fig. 15, which depicts the life cycle of a typical secondary cell, suggests periodic undulations in a persistent echo mass rather than the establishment of new cells as was the case in the smaller shear storms. The panels in the figure are spaced 4 min apart and a new secondary cell has appeared in Fig. 15b. The final panel presents the situation 16 min after that of the first, one minute shy of the observed cellular development cycle of 17 min.

Figure 16 portrays vertical velocity fields corresponding to the times in Fig. 15. We have concentrated on a 20 km section of the domain encompassing the leading edge and have superimposed the instantaneous system-relative airflow on the panels of this figure. It can be seen that, in contrast to the classic multicell or strongly evolving mode, the updrafts of the successive cells remained essentially connected. Figure 17, reproduced from Foote and Frank (1983), demonstrates that this connection is fundamental to their definition of weak evolution. Updraft surges began at low-levels and rose upward with time, following the same path without altering the tilt of the system’s airflow significantly. This trait, common to all secondary developments, is best demonstrated in this figure.

It was noted earlier that the development of a major cell was associated with the incorporation of low $\theta_e$ air from the forward side into the storm. This did not occur
Fig. 12. Rainfall intensity diagram for the $\Delta u = 10$ case. Plot starts at 448 min; maximum rainfall rate was 126 mm h$^{-1}$. See caption of Fig. 7 for more details.

Fig. 13. Rainfall intensity diagram for the $\Delta u = 22.5$ case. Plot starts at 718 min; maximum rainfall rate was 109 mm h$^{-1}$. See caption of Fig. 7 for more details.
during the mature phase of this simulation since no major cells formed. Figure 18 shows the $\theta_e$ fields corresponding to the panels of Fig. 16; for emphasis, the zones of air with $\theta_e < 327$ K have been stippled on Fig. 16 as well. As in all the other simulations, the development of a new cell, whether major or secondary, was associated with an upward surge of high $\theta_e$ (>333 K) from low-levels into the front-to-rear jet as the updraft cell intensified (Fig. 18a). While the mixing of low $\theta_e$ air into the updraft at high levels, suggested by the airflow, may have played a role along with water loading in degrading the top of the draft, no path appeared at any time between the surges that would have allowed this air to enter the storm’s downdraft layer; the current of high $\theta_e$ air rising within the updraft from the low-level environment remained unbroken across time. This is interesting because, unlike the lower shear cases, this storm never produced any strong low-level ($z < 4.5$ km) downdrafts at all. While low-level drafts with descending motion as strong as $-8$ m s$^{-1}$ appeared within the rain shaft after the low $\theta_e$ ingestion in the $\Delta u = 20$ simulation, the most intense draft ever to appear there in this case was $-2$ m s$^{-1}$ (although stronger downdrafts than can be seen at higher levels in Fig. 16).

Earlier, it was stated that the simulations with $\Delta u \geq 25$ failed to reach a mature state when started with an initial thermal. Instead, the cloud systems fell apart during their downshear oriented stages early in the simulations. It appears that, in each case, cold surface air created by evaporation of rainwater falling from the cloud was swept away by the strong winds in the shear layer faster than the developing cloud could replenish it and therefore subsequent redevelopments could not occur. In any case, the upward flow of low-level air into the cloud was cut off, starving the cloud of moisture and necessitating its decay.

A test was performed to see if the $\Delta u = 25$ model storm would have been able to survive if a different initialization method had been used. Usually, cloud modelers assume that the method of initialization is not critical to the final result since the decay time scales of typical initial conditions used are small relative to the characteristic time scales of the phenomena being
modeled (e.g., Smolarkiewicz and Clark 1985). It was reported in FO that the mature state reached by an ice-free model storm initialized with a heat sink styled after that employed by Thorpe et al. (1982) was quite similar to that of the conventionally initiated run they presented in all important aspects. At the same time,
FIG. 16. Vertical velocity fields for the $\Delta u = 22.5$ case; contour interval of 2 m s$^{-1}$. Regions with air of low equivalent potential temperature ($<327$ K) are stippled. Superimposed is system-relative instantaneous airflow vectors. Times of panels as in Fig. 15; due to the repetitiveness of the simulation, the panel corresponding to the time of Fig. 15e (798 min) is not shown. Only a portion of the subdomain shown in Fig. 15 is reproduced here.
however, it has been demonstrated that the final states achieved in many fluid systems may display "hysteresis," which is reflected by considerable sensitivity to the characteristic details of the startup procedure. For example, Ogura (1971) found that the preferred horizontal wavelength of finite amplitude Benard-Rayleigh convection does depend on the initial conditions. Similarly, Mak (1989) found multiple final states exist for the same external conditions in a baroclinic model.

In FO, we reported that the use of the heat sink initialization method resulted in accelerated development of the model storm since it provided the storm with a surface cold pool from the very start instead of forcing the system to develop its own. In the $\Delta u = 25$ case, it was thought that speeding the pace of development might have resulted in the convection becoming rooted before the high winds in the shear layer had a chance to tear the developing system apart. Like the thermally induced model storm, however, a simulation initialized with a heat sink did not survive to achieve a mature state. This storm did live a little longer, and did generate a series of cells. Unlike the smaller shear simulations, though, these cells appeared during the downshear tilting phase and propagated in the downshear direction. Each successive cell was weaker and the storm was essentially dead by 150 min, before it could develop a storm-relative upshear tilt.

We were, however, able to create a viable, long-lasting system with the $\Delta u = 25$ profile (as well as with even more strongly sheared cases) when the simulation...
\( \Delta u = 22.5 \quad \theta_e (K) \)

**Fig. 18.** As in Fig. 16 but for the equivalent potential temperature alone. Contour interval is 3 K. Note that the zone of low equivalent potential temperature air on the front (right) side of the updraft is trapped and unable to enter into the storm.
was initialized with the $\Delta u = 22.5$ run at a time which was well into its mature phase (at 14 h, the time at the top edge of Fig. 13). The environmental wind shear was increased slowly, over the period of 1 hour, and the simulation was then integrated for another 90 min, during which the storm was able to settle down. The resulting storm was quite similar to the $\Delta u = 22.5$ in general structure, except that it moved more quickly, the storm's updrafts were a little stronger, and the amplitude of the cellular precipitation maximum over the background rate was even smaller. The propagation speed attained by this model storm, 26.5 m s$^{-1}$, is consistent with the prediction of the $G-\Delta u$ relation (1), which originally had been constructed from storm speeds achieved by the model storms in the cases between $\Delta u = 10$ and 22.5, inclusive.

The continued decrease of the amplitude of the cellular oscillation led us to believe that a unicellular storm was perhaps attainable if the shear were increased sufficiently. The same rate of increase in the wind shear was used to create $\Delta u = 27.5$ and 30 model storms from the $\Delta u = 22.5$ case. These simulations were also integrated for a period of at least 90 min after the wind shear enhancement was terminated. While the precipitation patterns (not shown) produced by their storms were quite similar in structure to that of the $\Delta u = 22.5$ case, the temporal variations in their rainfall fields were greatly decreased. For the $\Delta u = 30$ storm, for instance, the difference between the largest and smallest maximum rainfall rates at any time within the cell development cycle was about 12 mm h$^{-1}$. This case generated as close to a steady, unicellular storm as we have been able to create in this model using the present model design and environmental sounding. Interestingly, the propagation speeds attained by the $\Delta u = 27.5$ and 30 cases, 28.3 and 30.1 m s$^{-1}$, respectively, were found to be those expected by (1).

We would like to anticipate and answer two possible objections to the above described subset of experiments. It can be argued that using the extremely strong wind shear intensities that these cases represent in a two-dimensional model is completely unrealistic since, if given the extra degree of freedom of the along-line direction, these storms would have developed highly three-dimensional structures. We agree with this statement but would reply by explaining that we wished, as much as possible, to fill out the wind shear spectrum under study, and that the study of the behavior of the model under these extreme conditions is of value. As an example of this, we find that the continued adherence of these highly sheared storms to the propagation speed/wind shear relationship (1) both interesting as well as a little disturbing since it requires explanation. One might also contend that the process of initializing these storms from lower shear cases during their mature phases has resulted in a set of simulations that is too incompatible with those initialized from a thermal to be of any use, due to the possibility of hysteresis. In the sense that we were unable to produce storms from typically used initial conditions for these cases, this is true and essentially impossible to test—at least on these cases. We would like to note, however, that we have been able to produce a storm that looks very much like the system that the $\Delta u = 22.5$ environment eventually developed, with respect to the transition in precipitation and secondary cell production, along with the essential storm propagation and circulation intensity characteristics, by starting with the $\Delta u = 20$ mature storm and following the same procedure of slowly increasing the shear. In addition, when we took the $\Delta u = 22.5$ case and slowly decreased the wind shear, we recovered a storm which again possessed major cells with attendant large rainfall bursts like the $\Delta u = 20$ case. These simulations tend to support the validity of the transition between the two shear intensities and provides additional, reassuring evidence that the mature state behavior is not a function of the initial conditions, at least for the $\Delta u \leq 22.5$ cases and the initial conditions we have tested. It is left for future work to find whether or not multiple equilibria exist for higher $\Delta u$ cases.

Figure 19 presents information about the temporal means and standard deviations of the domain maxima of vertical velocity during the mature phases of all of the model storms created for this study. It can be seen that the very low shear storms, $\Delta u < 7$, possessed relatively small maximum updrafts which did not strongly vary with time. This small variance was shared with the most highly sheared storms ($\Delta u \gg 22.5$), and between these two ends of the wind shear spectrum, the variances were substantially larger. In the low shear cases, the small standard deviations reflect the fact that these storms created individual cells at rather rapid rates even though each cell was quite discrete. In the

![FIG. 19. Plot showing the means (left-hand scale) and standard deviations (right-hand scale) of the mature phase domain maximum vertical velocity for all of the model simulations.](image-url)
larger shear cases, the small variance was due to the connection between cells and the fact that they were but small perturbations imposed on a persistent, quasi-steady state updraft.

It can also be seen in Fig. 19 that the average maximum updraft itself generally increased with the wind shear. The $\Delta u = 7.5$ case again has represented an exception to the general progression within the range of shear considered, and again the result does not appear to be an artifact. The decrease in the mean updraft between this case and the $\Delta u = 10$ storm could be explained, at least in part, by the fact that as the shear increased, alternate developments became weaker (i.e., more secondary) as the equilibrium state became more complex.

An intercomparison of the reflectivity and precipitation diagrams already presented shows that echoes associated with major cells in the more highly sheared environments traveled rearward more slowly relative to the storm’s leading edge, a result which has also been found in the three-dimensional simulations of Weisman et al. (1988). Figure 20 tracks cell positions relative to the gust front with time for three of the cases. These tracks were obtained by following the storm’s updraft maximum with time as it rose upward in the front-to-rear flow. For the $\Delta u = 5$ case, the cell gradually became distinguishable from the ever present updraft produced by forced lifting at the gust front and then propagated quickly rearward. Cell tracks for the other two model storms (the 12.5 and 20 runs) started with discrete major cells and the changes in direction occurred during the establishment of secondary cells, which were then tracked instead. It can be seen that these minor cells were created farther behind the leading edge than the major cells; this was also clear in FO’s Fig. 6 as well as in these reflectivity and precipitation diagrams. The separation speed between the major cell and the gust front clearly decreased with intensifying shear. Figure 21a shows that the ground-relative cell speed of the major cell approached $G$ as the shear increased. A very similar trend can be detected in Weisman et al. (1988; Fig. 13) for their $\Delta u = 0$ to 17 m s$^{-1}$ cases; for larger shear, they found cell and gust front speeds to be virtually the same.

This decrease in separation speed occurred despite the fact that both the time-averaged updraft and the front-to-rear relative flow strengthened as $\Delta u$ increased.

The latter can be seen in Fig. 22, which presents time-averaged fields of system-relative horizontal velocity for the $\Delta u = 5, 12.5, 20$ and 22.5 cases. Maximum system-relative rearward velocities increased from 18 to 33 m s$^{-1}$ across the range of cases, but the more vertical updraft orientation evident in the higher shear cases in this figure (and in Fig. 26, to be described later) shows that the major cells rose upward more quickly after initiation. Figure 20 demonstrates that they survived only over a narrower horizontal distance behind the gust front, confirming impressions already gained from the reflectivity and precipitation diagrams. Therefore, the more rapid vertical displacement of the cells accounts for the smaller separation speeds in the more highly sheared cases.

These cell speed estimates are naturally sensitive to the specific method with which they were obtained. Different features move at different rates within the storm. Using our definition, however, we can note that systematic relationships exist between both the separation speed and the system-relative midlevel environmental inflow (Fig. 21b) and the cell speed and the shear (Fig. 21c). In fact, the former suggests that the separation speed is consistently close to twice the intensity of the prestorm (or remote) midlevel inflow ($\Delta u - G$), as marked on the figure. Since the cell updrafts were moving within the front-to-rear jet, which consisted of air which was drawn primarily from low levels (especially in the larger shear cases), it is not entirely clear why such a relationship should be meaningful. The low shear cases did have significant midlevel inflow, however, due to the large differences between $\Delta u$ and $G$, and the simulations of Dudhia et al. (1987) have demonstrated that the winds at midlevels can have an important impact on storm structure and cell motion.

The two-dimensionality of the model probably had an important influence on these cell speed statistics since we note that in their 3D simulations, Weisman et al. (1988) found their cell motions to be more comparable to the speed of the inflow above the shear layer in their low-level shear experiments rather than twice the inflow intensity as in our case. In these 2D runs, air rising into the storm from the front side is not al-

![Fig. 20. Position of cell maximum updraft relative to the gust front with time from birth for typical cells from the $\Delta u = 5, 12.5$ and 20 cases. Cell tracks begin with the creation of a major cell. For the two higher shear cases, a sudden change in direction indicates that a secondary cell has been produced. The cells then were tracked until they became indistinct. For each case, only the cell(s) produced within a repeat cycle were followed.](image-url)
c. Storm scale, tilt and precipitation efficiency

The rainfall diagrams already presented suggested that the horizontal width of the precipitating portion of the model storms decreased with intensifying wind shear. As the storms contracted, the precipitation became more localized and concentrated closer to the leading edge. This transition can also be seen in Fig. 23a, which presents time-averaged precipitation rates with respect to the leading edge for the $\Delta u = 10$, 15 and 20 model storms. The general tendency was for the greatest rainfall rates developed by the model storms to be larger for the more highly sheared runs. Exceptions to this, however, existed in both tails of the wind shear spectrum we have considered here. On Fig. 23b, the curves of Fig. 23a have been reproduced and augmented with data from the $\Delta u = 5$, 7.5 and 22.5 cases. The largest average precipitation rate in the $\Delta u = 5$ case was larger than in either the 7.5 or 10 storms, but was located well behind the gust front. The 7.5 case itself had an unusual rainfall distribution. The curve for the $\Delta u = 22.5$ storm appears to be very similar to that of the $\Delta u = 20$ case, but it has already been seen that the time-dependent behavior of the precipitation production between these two cases was quite different.

Despite the horizontal contraction, total precipitation reaching the surface generally increased with shear. Time-averaged total domain precipitation rates for the experiments are presented in Table 3. Also given in the table are prestorm or remote relative inflow rates of water vapor, determined from the initial moisture sounding and the wind profiles of the various experiments adjusted to be system-relative. The precipitation efficiency (PE) statistic listed is simply the rainfall rate divided by the remote vapor inflow. While the larger shear storms generally produced more precipitation than those with smaller shear, they also drew in water vapor at a faster rate since they propagated faster. As a result, these efficiency statistics betray no clear, systematic relationship with the low-level shear. All of the model storms were very efficient, perhaps due in part to the geometry of the model which places restrictions on where and how the inflowing moisture-laden air can spread.

The compilation of observations presented in Browning (1977; Fig. 24) suggested that more highly sheared storms should, in fact, be less efficient than their less sheared counterparts in generating precipitation. The shear considered in Browning was through the cloud layer rather than that confined to low levels as in our experiments. Also, it has been noted that these statistics were gathered mostly from High Plains storms, of which the majority were hailstorms. Indeed, recent analyses made by Fankhauser (1988) have suggested that the relationship between wind shear and precipitation efficiency is more complex than just a simple inverse relationship. In our experiments, the only cases that really stand out are the $\Delta u \approx 22.5$ runs,
which represented a separate regime, a shift from the intense yet intermittent precipitation of the lower shear storms to steadier producers of rainfall. This shift resulted in the least efficient storms of the series for the \( \Delta u = 22.5 \) and 25 cases, although the PEs of the next two simulations were quite high.

These PE values are naturally dependent on the way they were computed. Many observational studies have tried to estimate the vapor influx into the cloud by using sounding or aircraft data taken in the immediate vicinity of the storm. In our storms, the remote vapor inflow is an underestimate of this vapor influx since in each case the environmental winds approaching the storm were enhanced further in a manner consistent with the mesoscale pressure field (for example, see FO's Fig. 11c) and balancing the high-level forward anvil outflow. The forward outflows in these cases, however, were not as strong as they were in the model storms of FO, which had some wind shear through the lowest 7 km (Fig. 22; FO's Fig. 10c). One could make use of the data of Table 3 and note that, among these cases, the fraction of the net condensation which resulted in

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**Fig. 22.** As in Fig. 4 but for the system-relative horizontal velocity; again, the panels (a) through (d) are the \( \Delta u = 5, 12.5, 20 \) and 22.5 cases, respectively. Contour interval is 3 m s\(^{-1}\). On each panel, the outlines of the cold pools from Fig. 4 have been superimposed.
TABLE 3. Statistics concerning precipitation production.

<table>
<thead>
<tr>
<th>Low-level shear</th>
<th>Remote vapor inflow</th>
<th>Surface rainfall</th>
<th>Net condensation</th>
<th>Rain evaporation</th>
<th>PE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>282.3</td>
<td>214.6</td>
<td>330.3</td>
<td>103.9</td>
<td>76</td>
</tr>
<tr>
<td>7.5</td>
<td>349.5</td>
<td>246.3</td>
<td>384.4</td>
<td>136.6</td>
<td>71</td>
</tr>
<tr>
<td>10.0</td>
<td>330.4</td>
<td>240.3</td>
<td>389.7</td>
<td>143.7</td>
<td>73</td>
</tr>
<tr>
<td>12.5</td>
<td>339.4</td>
<td>241.9</td>
<td>391.6</td>
<td>146.1</td>
<td>74</td>
</tr>
<tr>
<td>15.0</td>
<td>351.3</td>
<td>253.0</td>
<td>412.0</td>
<td>153.0</td>
<td>72</td>
</tr>
<tr>
<td>17.5</td>
<td>361.5</td>
<td>272.1</td>
<td>444.7</td>
<td>155.0</td>
<td>75</td>
</tr>
<tr>
<td>20.0</td>
<td>383.6</td>
<td>291.1</td>
<td>463.0</td>
<td>170.0</td>
<td>76</td>
</tr>
<tr>
<td>22.5</td>
<td>405.1</td>
<td>274.8</td>
<td>471.0</td>
<td>185.2</td>
<td>68</td>
</tr>
<tr>
<td>(25.0)</td>
<td>415.3</td>
<td>282.0</td>
<td>474.9</td>
<td>183.3</td>
<td>68</td>
</tr>
<tr>
<td>(27.5)</td>
<td>428.9</td>
<td>319.3</td>
<td>520.6</td>
<td>202.0</td>
<td>75</td>
</tr>
<tr>
<td>(30.0)</td>
<td>443.4</td>
<td>354.2</td>
<td>564.7</td>
<td>217.8</td>
<td>80</td>
</tr>
</tbody>
</table>

![Fig. 23. Mature phase time-averaged precipitation rates (mm h⁻¹) plotted as a function of distance from the gust front. The curves of panel (a) are for the Δu = 10, 15 and 20 cases. These curves have been reproduced as solid lines on panel (b) which emphasizes data from the more extreme (Δu = 5, 7.5 and 22.5) cases.](image)

Surface rainfall varied even less than did the PE, ranging from 58% to 65% with an average of 62%. The constancy of this statistic across the wind shear range suggests that the setup of the microphysical parameterization itself might be a major controlling factor in the results. Model PEs were found to be far more sensitive to alterations in the "knobs" in the microphysics (such as autoconversion rates and actuation thresholds, as well as particle distribution parameters) than to the intensity of the low-level wind shear.

It was noted in the Introduction that FO determined that the major dynamical impact of the inclusion of ice was to allow the basic features of the storm to increase in scale. This increase was attributed to the larger rearward transport of condensate, chiefly snow crystals, in the front-to-rear jet which characterized the ice model simulations. Low density snow particles were depleted, through fallout and scavenging, from the rearward flow at a slower rate with distance from the leading edge, allowing the cooling resulting from their changing state to be spread farther as well. This cooling more than compensated for the subsidence warming due to downdrafts in the convective region of the model storm.

A portion of the enhancement in the rearward flux was probably due to the generally stronger front-to-rear airflow in the ice model storms. In the present simulations, however, the stronger front-to-rear jets in the more highly sheared storms did not result in greater rearward transports of condensed water particles. On

![Fig. 24. Time-averaged system-relative horizontal mass fluxes (kg m⁻¹ s⁻¹) plotted against height for the Δu = 5 (dotted line), 12.5 (dash-dotted line) and 20 (solid line) cases. Calculated for a vertical section 70 km behind the gust front for each case. Positive values denote inflow into the storm from the rear.](image)
the contrary, the rearward flux was depleted more quickly in these cases, consistent with the narrower widths of the storms, despite the fact that more intense updrafts which condensed vapor at larger rates were produced. Cells reached their intense rainfall stage at positions increasingly closer to the leading edge. In addition, stronger rear-to-front flow beneath the rearward jet helped to sweep the rainwater falling from the cells back towards the leading edge, concentrating both the surface precipitation and the evaporative cooling into increasingly narrower, more sharply defined zones.

This rear-to-front airflow in the subcloud zone was part of the rear inflow current. As in the model storms described in FO, air parcels in the currents could travel through the subsidence region over the body of the cold pool and descend into the pool as the pool itself deepened. Both the intensity and the depth of the airflow within the current increased with the shear; this can be seen in Fig. 22. The $\Delta u = 5$ case (Fig. 22a) had a weak system-relative rear inflow current which descended into the cold pool at about $x = 25$, a considerable distance behind the gust front location. This air was forced to descend as it entered the low-level downdrafts which occurred beneath the cells in their rain shafts. The other panels in this figure show that the intensity of the current increased with the shear and the point where the current breached the cold pool moved closer to the leading edge.

As a result, as the shear was strengthened, subsidence region air which was itself increasingly somewhat warmer and drier was being advected into the subcloud cold pool at an ever greater rate. Note also that the top of the system-relative inflow current ascends as the shear is increased so that the source region for the current is also progressively more potentially cold. We suspect that these factors at least partly explain the rise in rainwater evaporation rates which occurred as the shear was increased (Table 3). Enhanced evaporational cooling in the subcloud region, combined with greater condensation (and rainwater production) rates along with an airflow that appears to have helped pile up this air behind the gust front, resulted in the creation of deeper and colder outflow cold pools. The higher surface buoyancy pressures that directly resulted from this in turn produced faster propagation speeds, as already investigated.

Therefore, it appears that the rear inflow current has played a role, directly or indirectly, in organizing the model storm. FO reported that the location of the rear inflow current is attributable to the system-wide horizontal pressure gradients and speculated that it was intensified by the severe mass continuity constraints of the 2D model. In fact, the present experiments strongly suggest that mass continuity does play a crucial role in determining the specific intensity of this feature in any given case. The systematic relationships among the shear, propagation speed $G$ and the average surface buoyancy pressure previously investigated then make a similar relationship between the shear and the intensity of the rear inflow current unsurprising. It appears that the rear inflow current, forced (at least in part) by the constraints of mass continuity to increase in magnitude with intensifying shear and the prime source of air which helps induce evaporation in the subcloud cold pool, may have been the major contributing factor in bringing about the systematic relationship between $\Delta u$ and $G$, particularly since the only difference among the simulations was the shear profile.

It should be noted here that we are not concerned about the general result of the current intensity increasing with shear. The stronger storms, which the more highly sheared environments supported logically, tended to have stronger circulations in general; this includes the strength of the inflow current. Rather, it is the very systematic behavior across the wind shear spectrum that begs for explanation. Figure 24 depicts system-relative horizontal mass fluxes as a function of height in the model troposphere computed for the $\Delta u = 5, 12.5$ and 20 cases at a standard location taken to be 70 km behind the gust front. This location corresponds to the left sides of the plots in Fig. 22. It can be seen that the maximum intensity of the front-to-rear jet, located at heights between 6 and 8 km, increased with the shear while the layer depth decreased. Our computations indicate that to a reasonable approximation the system-relative mass flux in this layer can be taken to be roughly constant among these model storms. For the $\Delta u = 5, 12.5$ and 20 cases in Fig. 24, the mass fluxes in the front-to-rear jet at the standard location, within the model troposphere, were $5.46 \times 10^4$, $5.13 \times 10^4$ and $5.19 \times 10^4$ kg m$^{-1}$ s$^{-1}$, respectively; the average over all cases was close to $5.11 \times 10^4$. In addition, the model storms displayed a tendency to recover system-relative surface wind speeds approximately the same as those in the inflow environment (i.e., $-G$) in the body of the cold pool by 70 km behind the front. (The vertical wind shear within the body was larger than in the inflow environment since the depth of the cold air in this zone was in all cases less than that of the shear layer, although it did increase with $\Delta u$.) At the same location, the relative winds at the top of the pool were usually very nearly calm and therefore a good approximation of the layer average wind is $-G/2$. Since the mass inflow rate through the depth of the domain ahead of the storm is known for each case, and the mass flux through the front-to-rear jet was about the same among the experiments, the increasingly intense rearward flux in the body of the cold pool with larger $\Delta u$ must have occurred in tandem with further enhancement in the mass transport within the rear inflow current. Indeed, since the interface of a well developed outflow was relatively impermeable, the air moving rearward within the body of the cold pool could reasonably be approximated as the return flow of air which had entered in the rear inflow current.
This argument is complicated by two factors. The depth of the rear inflow layer became shallower as $\Delta u$ increased. Also, the system-relative mass inflow through the total domain depth ahead of the storm actually increased as the shear was lessened, although less of it was concentrated at low-levels. These facts do not spoil the above argument, though, as can be seen in Fig. 25, which demonstrates the high positive correlation between the layer-average intensity of the rear inflow current and the wind shear. The intensities plotted were obtained from time-averaged statistics taken at the standard location. It is interesting to remember that these intensities are system-relative; this implies that, especially for the larger shear cases, the rear inflows which developed were very strong when considered in a ground-relative frame of reference, too large to be considered as environmental features that have caught up with the storms from behind. In any case, it was noted by FO that the currents developed from the front towards the rear with time.

Related to the inflow current intensity question is the vertical tilt of the front-to-rear storm circulation which draws low-level air from ahead of the storm and expels it out at high levels to the rear. One might think that a narrower, more intense storm would have a more vertically oriented circulation and this is in fact what occurred. Figure 26 presents time-averaged airflow diagrams for the cases under closer study. The larger shear storms had deeper, more sharply defined cold pools and this perhaps helped to set up more vertically tilted inflows. It is important to remember that these are time-averaged fields; in the smaller $\Delta u$ cases, the individual cells represented very large perturbations upon the time-averaged front-to-rear circulation.

In their analysis of two 2D simulations, one multicellular and one unicellular, Dudhia et al. (1987) speculated that the surface cooling was larger in their multicell storm due to the fact that its airflow was less vertically oriented. They reasoned that because precipitation was spread over a wider area behind the storm, parcels in the downdraft could experience cooling due to evaporation for a longer period of time and over a wider area. Their unicell storm was quite different in its basic structure than their multicell, however, in that the former never actually generated a cold, subcloud outflow. In contrast, our results suggested that the more vertically oriented storms were associated with colder subcloud temperatures. No storm similar to their unicell was produced; in this sense, the basic structures of the model storms we have created are all the same. It should be noted, however, that the structures of the employed vertical wind profiles are quite different between the two studies.

We do not mean to suggest, however, that the rear inflow current alone participated in determining the tilt of the model storm's circulation. It can be noted in Fig. 3b that the intensity of the midlevel headwind relative to the low-level inflow decreased as the shear was increased. An increasingly intense storm-relative low-level flow, coupled with diminishing midlevel headwinds, should set up a more vertically oriented circulation after impinging upon a substantially impermeable obstacle like the model storm cold pool. The transition between strong and weak evolution in the model storms, as well as the general increase in the period of the repeat cycle, can perhaps be related to the diminishing strength of the headwinds that can force low $\theta_e$ air into the storm. With the present sounding and model setup, this transition was found to exist at very large shear intensities. Increasing the within-cloud turbulent mixing, however, was found to induce this transition to occur at more moderate shear intensities, as mixing generally opposed the cell separation that allowed the low $\theta_e$ air from the front side to slip into the storm. We are satisfied, therefore, that the transition is not a phenomenon produced solely under conditions of extremely large shear where the applicability of two-dimensional models is suspect.

The behavior noted here, that the tilt of the circulation became more vertical as the shear was increased, is the opposite of that found in the analytical model of Xu and Chang (1987). They found that, except when the lifting condensation level was specified to be quite high, the tilt decreased along with the Richardson number $Ri$. Since the CAPE, the numerator of the $Ri$ ratio, was unchanged among the experiments, our results indicate that the tilt increased for decreasing $Ri$. This apparent contradiction requires further investigation.

5. Further discussion

a. RKW theory and the lack of model storm decay

Recently, Rotunno et al. (1988, hereafter RKW) proposed a theory to explain the observed fine-normal
circulation tendencies (including updraft orientation or tilt) of organized squall lines. They started with the Boussinesq horizontal vorticity equation in two dimensions and, after invoking a number of simplifications and approximations, they derived the following expression

\[ \Delta u = c \]  \hspace{1cm} (4)

where \( c \) was related to the theoretical propagation speed of a density current under ideal conditions (i.e., \( c = kU^* \) with \( k = 2^{1/2} \)). They interpreted (4) as representing an "optimal state" of balance between the positive horizontal vorticity associated with the shear profile and the negative horizontal vorticity produced by the cold subcloud pool of air. Equation (4) was derived after specifying that the airflow striking the cold pool would be turned vertically, that there was no positive buoyancy (i.e., cloud) above the outflow head, and that no motion occurred within the cold pool itself. When the latter specification was relaxed, a more complicated expression was found.

RKW concluded that the \( \Delta u < c \) case represents a "less than optimal" condition in which the circulation
set up by the cold outflow is too strong for the given amount of environmental shear. They characterized this state as possessing an updraft that tilts upshear (rearward) with height, the orientation achieved by our storms in their mature phases. While less conducive to inducing deep, concentrated lifting than the vertically oriented optimal updraft, this upshear tilting configuration is usually thought of as being efficient or favorable because precipitation falling from the updraft is not able to contaminate the inflowing air feeding it. Indeed, our simulations show that as long as air parcels forced to rise over the cold pool can achieve free convection, the storm can continue to survive through the establishment of new cells.

That the mature phases of our model storms were all less than optimal can perhaps be demonstrated by noting again that the low-level shear was exceeded by the storm propagation speed in each case (i.e., \( \Delta u < G \)). We are assuming here that we can consider the two speeds \( G \) and \( c \) to be the same; this requires a more direct relationship between these two variables than we have been able to establish. We believe, however, that we may say that the mature model storm condition approached RKW's "optimal state" as the shear was increased. The data of Table 1 showed that the gap between \( \Delta u \) and \( G \) generally decreased as the shear was increased. This culminated in the \( \Delta u = 30 \) case in which, for all practical purposes, \( \Delta u = G \). Recall that at the same time the slope of the updraft was becoming more vertically oriented (Fig. 26); RKW's optimal state was based on the assumption that the flow impinging on the cold pool was turned vertically.

On the basis of our model simulations, we suggest that the less than optimal state represents the multicell regime. Simulations which could be considered to be in states far below what RKW would consider optimal (small \( \Delta u \)) were typified by model storms which fit the classic multicell model very well. The nearly optimal run (\( \Delta u = 30 \)) was a weakly evolving storm that in some senses could be considered as unsteady unicell. Model storms with strong low-level shear also had strong rear inflow currents which appears to have helped 'prop up' the storm's updraft; the weak inflow at midelevles on the forward side in these cases may have provided less of a rearward push on the individual cells, helping to blur the distinction between them.

As in FO, we are again moved to consider why none of our model storms evinced a terminal decaying phase as such storms do in reality. Indeed, one of the motivations behind performing this set of simulations was the suspicion that the environmental conditions of FO's simulations were, fortuitous accident or design of nature, sufficiently close to an optimal balance (in the RKW sense) between the thermodynamics and dynamics that the achievement of an essentially permanent mature state was proper and to be expected. We considered the possibility that, because FO's model storms produced rather strong cold air outflows, if we were to decrease the wind shear impinging on the cold pool we might then produce a storm that displayed the entire life cycle of a squall line within this simple two-dimensional framework. We found, however, that the small shear cases produced cold pools which were much weaker and shallower than those generated by the larger shear storms, even though the thermodynamic portions of the initial environmental conditions were the same across the experiments. Although demonstrably farther from the RKW optimal state, they were still able to organize themselves into mature states marked by very long-lasting, relatively repetitive behavior. It is clear that the thermodynamics have adapted to (or participated with) the ambient wind shear in determining the resulting mature state.

Our simulations and interpretations differ from those shown in and advanced by RKW and Weisman et al. (1988) in several important ways. Their model storms did not attain mature stages marked by quasi-equilibrium behavior as ours did; rather, most (if not all) of their storms did suffer a phase of slow decay with time. The slowly decaying phase, which began earliest in the smallest shear cases which were farthest from the optimal state, comprised a period in which the updraft became progressively more tilted in the upshear direction. In their conclusion, Weisman et al. (1988) interpreted the decaying phase and progressively greater system tilt to be consequences of an imbalance between the cold pool and the shear which was becoming even more unfavorable with time. Clearly, this is very different from the situation we have found. Our mature phases were, by definition, marked by quasi-equilibrium behavior that was statistically steady over time periods much longer than those represented by the cellular redevelopments. This steadiness applied to all aspects of the storm and its circulation features, including the strength of the cold pool. Therefore, we have chosen to interpret the less than optimal condition as one which causes the model storm to be weaker and more clearly multicellular, but also at the same time one which is not necessarily fatal or terminal.

It should be recognized that we are using input thermodynamic conditions which are very conducive to producing (and maintaining) convection. Experience has shown that there are several aspects of our input sounding which are extremely favorable. The first is a low-level temperature lapse rate which is nearly dry adiabatic between the surface and the level of free convection; this shields a parcel rising from the surface from being subjected to negative buoyancy on its way up into the storm. This might be important in the low shear cases which possessed updrafts which were strongly sloped in the horizontal. Important also is the combination of relative dryness near the surface with high humidities near cloud base; the former promotes the development of a strong cold pool and the latter helps the rising inflow achieve and maintain saturation. Yet these features are also commonly found in,
for example, typical severe Oklahoma storms (cf. Bluestein and Jain 1985).

Finally, we need to point out that, for the cases we are simulating, the long-lasting quasi-equilibrium state has not been found to be absolutely permanent. Sensitivity tests conducted thus far, however, have indicated that departures from permanence in our model have been brought about by numerical rather than physical forcings. Naturally, a dynamically consistent model will respond to any such forcing in a dynamically interpretable manner and thus it becomes a matter of separating the numerical from the physical mechanisms. While the precipitating portion of a model storm was found to develop an equilibrium width in each case in our model, other portions of the storm, most notably its front-to-rear airflow, continued to slowly expand in the flanking stretched grid regions. These regions, by their very nature, act to dissipate the perturbed flow caused by the convection, and thus had their greatest effect on the more highly sheared cases since they possessed the stronger perturbations. This is important because, for example, long-term alterations of the airflow within the trailing stretched grid region can be communicated back into the leading portion of the storm through the influence of the rear inflow current and thereby eventually bring about changes in the storm's structure or behavior. These changes can be misinterpreted as physically realistic if sufficient sensitivity testing is not performed. The major features we have discussed in this paper, such as the propagation speeds, rainfall estimates, the lengthening of the repeat cycles with shear, the transition in temporal behavior at the high shear end of the spectrum and, especially, the lack of a physically realistic decaying stage all have survived extensive sensitivity testing.

Therefore, while more work along the lines of Nicholls et al. (1988) needs to be done in order to evaluate the influences of various sounding properties on resulting storm intensities and structures, we believe we can conclude here that, for this sounding, the seeds of the storm system's decay are not contained in the storm itself for the present limited physical framework. It is important to recognize that this limited framework has excluded the influences of Coriolis accelerations, horizontal inhomogeneities in the base state environment, forcings external to the storm such as radiational cooling and other diurnal effects and the third spatial dimension. Any or all of these limitations may turn out to be important factors that control a real storm system's lifecycle, but we reiterate here the comment of FO: We believe that one needs to demonstrate that the decaying phase of any model storm obtained was not numerically determined.

b. Schematic model

Within our two-dimensional context, we present Fig. 27, a schematic model of our simulated storms, synthesizing the time-averaged structures presented in this work and in FO. The features presented are at least in qualitative agreement with observations and other numerical simulations; the horizontal and vertical scaling of the figure is not intended to be precise. The outline of the cold pool is depicted on the figure as the thick, black line and is characterized by an elevated head at the leading edge and an extended, shallower body at the rear. Also depicted on the figure is the rear inflow current which breaches the cold pool behind the head, splitting into two branches as it hits the ground.

The rearward branch has been termed the overturning downdraft (e.g., Dudhia et al. 1987). The forward branch encounters incoming flow from the environment at the gust front, dynamically forcing high pressure and a turning of the airflow on both sides of the cold air boundary. High pressure at the surface farther to the rear, beneath the head region, is associated with buoyancy pressure reflecting the weight of the cold air piled up in the head. Also depicted on the figure is a path for low $\theta_e$ air to enter the cold pool from the mid-level environment on the forward side, a situation which occurs during the birth of major cells in our simulations which produced such cells.

A close examination of Figs. 22 and 26 shows that the gust front boundaries in the model storms were not perfectly impermeable. Instead, there appears to be a mixing zone between the cold pool air and the air in the environment which is heading into the updraft at and just behind the nose of the cold pool. That such mixing did actually occur in our model storms can be demonstrated by noting that the net condensation rates listed in Table 3 exceed the remote vapor inflow in every case. Because of a net loss of vapor through the back of the storm in each case, the vapor convergence rate into the storm area was even smaller than the remote inflow. Since the moisture variables were handled in a conservative manner, this implies that some of the vapor produced by the evaporation of rainwater in the subcloud outflow must have found its way back into the
updraft to account for the observed condensation rates. While a mixing zone between an outflow and the ambient environment is usually included in schematic models of thunderstorm outflows (e.g., Fig. 28 in Wakimoto 1982; Fig. 1 in Goff 1975), this mixing takes place along the outflow's upper surface and is induced by Kelvin–Helmholtz instability, a process which takes place at scales too small to resolve on our grid. If this simulated mixing is excessive, it may be due to the relatively coarse resolution (compared to numerical outflow models like DW's) and the use of centered finite difference schemes (which have difficulty preserving large gradients).

In FO, the limited, quasi-stable horizontal widths of the model storms attained during their mature phases was attributed to the finite rearward flux of condensate in the front-to-rear flow from the source region behind the leading edge. While this flux was alterable by manipulating the microphysics, an equilibrium width was obtained in each case. The experiments described herein demonstrated that the vertical wind shear also participates in determining the scale of the convective region of a model storm. While the larger shear cases produced stronger system-relative front-to-rear airflows, these did not translate into larger rearward precipitation fluxes. Their updrafts were more vertically oriented than in the smaller shear storms with the result that the precipitation was concentrated more closely to the leading edge. A portion of this concentration was due to the force of the rear-to-front flow in the cold pool, the intensity of which was a function of shear due to mass continuity constraints. This current appears to have played a role since it advected dry air into the subcloud cold pool, probably resulting in the observed enhancement of the evaporation rate which occurred in the larger shear storms. We can see a balance between the opposing forces of the front-to-rear precipitation flux in the cloud and the dry rear inflow in determining the scale of the model storm.

c. Timing between successive cells

While the fundamental scale of the storm was greatly affected by the low-level shear, the intrinsic period between individual cells (both major and secondary) was little changed. The time interval between major cells, which were new, dynamically distinct updrafts as in the classic multicell mode, increased with $\Delta u$, but the gaps between were filled by minor or secondary cells with the result that the average period between storm reintensifications (whether major or minor) was relatively constant across the wind shear range considered. Thorpe et al. (1982) suggested that the periodic development of cells in multicellular storms was controlled by buoyancy oscillations associated with the forced lifting of warm, moist air over an obstacle like the cold outflow. Indeed, our results suggest the existence of a fundamental oscillation common to the model storms which is progressively masked as the shear was increased, and the repeat cycles are likely to be influenced in part by temporal undulations in the cold pool surface associated with time-dependent airflow variations within it. Sensitivity testing has been performed in order to ascertain the validity of these model storm oscillations. As in FO, we have concluded that the essential elements of the repeat cycles the model storms display, including their existence and their tendency to increase in length with the shear, are reasonable and the smaller amplitude, much longer period variations which were sometimes superimposed upon them are spurious and unimportant.

6. Summary

The simulations described herein were made to gauge the effect of vertical wind shear on the convection produced in a two-dimensional model, extending the previous work of the authors (Fovell and Ogura 1988). We adopted a simple, linear shear profile, in which the shear was confined to low levels, similar to those chosen in the past by other modelers. Shear intensities over a wide range were considered, encompassing values typically associated with multicell type storms.

The majority of the model storms obtained were similar to those created by Fovell and Ogura in that they organized themselves into mature states consisting of repetitive development which has been termed "quasi-equilibrium" behavior. The length of the repeat cycle increased with the shear, going from about 12 min for the smallest shear intensity considered to essentially infinity for the most intense case. At the same time, the complexity of the cycles, as manifested in reflectivity and rainfall diagrams, also increased. The smaller shear storms generally were composed of a series of similar, discrete cells as in the classic multicell model but the discreteness was progressively lost as the shear was intensified. The more strongly sheared storms also propagated faster and generally resulted in more precipitation, although they were not very different from the smaller shear storms with respect to precipitation efficiency. A good relationship grounded in hydrostatics was found between the surface pressure jump across the gust front and the storm's speed of movement, as expected from density current theory and the laboratory work of Simpson and Britter (1980).

Indeed, the storm speed and the intensity of the shear were also found to be quite systematically related; this may be exacerbated by the influence of the model's geometry on the results. As the shear increased, so too did the intensity of the model storm's rear inflow current, also in a very systematic fashion. This feature transported dry air from the subsidence region at the rear of the storm into the storm's subcloud cold pool, enhancing the evaporation of rainwater in the pool and helping the more strongly sheared storms attain colder temperatures within the pool. This was hydrostatically
associated with faster propagation speeds, as noted previously.

The wind shear range considered appeared to encompass several different regimes among which model storm behavior varied markedly. The lowest intensities of shear considered produced weak storms which did not attain the same high degree of repetitiveness as did the larger shear simulations, in part due to random influences on their horizontally extensive, highly sloped updrafts. The medium shear range consisted of multicellular storms which fell within the category of what Foote and Frank (1983) termed “strong evolution”; each repeat cycle started with the establishment of a new, discrete cell updraft. In contrast, the largest shear cases showed the characteristics of “weak evolution” in that the discreteness between successive “cells” was completely lost. Instead of new updrafts, periodic reintensifications of a solitary, persistent updraft were taking place in each case, and the amplitude of these reintensifications decreased as the shear was intensified. The boundary between the strongly and weakly evolving modes appeared to be quite sharp within the wind shear spectrum and the temporal aspects of the storms’ precipitation production, as well as its processing of ambient low equivalent potential temperature air, were quite different between the two regimes. We noted that we were able to induce this transition at more moderate shears, where two-dimensional models have been shown to be more applicable, by manipulating model “knobs.”

We have also discussed these model results within the context of the recent theory advanced by Rotunno et al. (1988). They argued that an optimal state of balance exists between the positive horizontal vorticity of the vertical wind shear and the negative horizontal vorticity produced within the subcloud cold pool which results in a storm with a strong, vertically oriented updraft. We noted that, using their terminology, all of our model storms were less than optimal, consisting as they did of upshear tilting updrafts, and hastened to point out that departure from optimality did not instigate or necessitate decay in our simulations. We also noted that our storms approached the optimal state as the shear was increased, becoming stronger and more vertically oriented, an observation which is in agreement with their theory. At the same time, however, it was apparent that while the repeat cycle lengthened in period and increased in complexity as the shear was raised, the average period between reintensifications remained about the same. This suggests that the shear was masking a fundamental oscillation, common among the model storms, associated with the lifting of air over a persistent yet undulating cold pool.

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