A New Mechanism of Convective Cell Regeneration and Development Within a Two-Dimensional Multicell Storm*

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ABSTRACT

In this study, based on simulations of a two-dimensional multicell storm under a ground-layer upshear ($U_z < 0$) by a mesoscale numerical model, a new mechanism of cell regeneration and development within the multicell storm at the “less than optimal shear” state is proposed.

In the presence of a ground-layer upshear, the circulation associated with the surface cold pool is not counteracted by that associated with the ambient wind shear, and the density current extends out faster, making the multicell storm stay at the “less than optimal shear” state. As a result, a new cell is triggered by the strong vertical perturbation ahead of the mature convection, rather than by the split-up from the updraft at the leading edge of the surface cold pool as well as the gust front. The latter is the mechanism at the “optimal” state proposed by Lin et al. in 1998. In the new mechanism, the regenerated cell grows fast with the incident warm moist air from the upstream of the multicell storm, and tends to cut off the moist airflow into the mature convection at its western sector. Consequently, the mature convection would weaken, be replaced, and eventually decay.

Actually, these two different mechanisms come into play in a way depending on the relationship between the circulation of the low-level shear and that of the cold pool. When the circulation of the cold pool is stronger than that of the wind shear, the multicell storm is at the “less than optimal shear” state, and the new convective cell is produced by the disturbance ahead of the mature cell. When the circulation of the cold pool is weaker, the cell regeneration is dominated by the mechanism at the “optimal” state, and the new cell is split from the gust front updraft. Therefore, these two mechanisms are not contradictory. With a moderate ground-layer upshear, they can alternately operate within a multicell storm.

Key words: multicell storm, squall line, low-level shear, cold pool, convective cell


1. Introduction

The squall line as a typical mesoscale convective system has been widely studied for several decades. However, due to its distinctive features, such as short lifetime, concentrated and intense convective rainfall, etc., it is still difficult to forecast and make early warnings of this type of weather at present. The convective storms, according to the mechanisms of new cell regeneration and development, degree of severity, longevity and intensity of precipitation, have been classified into three types by Fovell and Ogura (1988): (1) the short-lived single convective cell, (2) the discretely propagating multicellular storm, and (3) the long-lived continuously propagating supercell. Among the three types, the multicell storm is the most common, and can last several hours owing to the regeneration and development of new convective cells. Precipitation from multicell storms often appears as a narrow, quasi-linear rainband made up of several short-lived single convective cells at four different evolutionary stages. Embedded within the “front to rear” cross section perpendicular to the rainband, the cell life stages are divided into the initiation, development, maturation, and dissipation, respectively.

There are two important questions raised in the

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investigations of a multicell storm: 1) how and why could the new convective cell regenerate? 2) how would the regenerated cell develop? Thorpe and Miller (1978) proposed that the new convective cell is produced by the convergence forced by the downdraft from the previous cell. In their study, this convergence that exists at the leading edge of the multicell storm is not persistent but periodic. Hane et al. (1987) also identified that the convergence is periodically enhanced by the spreading of the previous cell downdraft, as a manifestation of the cell cycle. Fovell and Ogura (1988, hereafter FO88), Fovell and Tan (1998, hereafter FT98), and Lin et al. (1998, hereafter L98) presented another argument: after a cold pool is created by the evaporation of hydrometeors falling from the previous cell and spreads rapidly along surface, the convergence at its leading edge could trigger a persistent gust front updraft (GUF) as a crucial factor to provide initial lifting to the new cell within the multicell storm.

Thorpe et al. (1982) indicated that the ambient vertical wind shear, especially low-level wind shear, is an important factor for the development and maintenance of the long-lived multicell storm. Rotunno et al. (1988, hereafter R88) demonstrated that, when the circulations associated with the cold pool and the ambient wind shear are near equal but of opposite signs, the GUF at the leading edge of the cold pool is the strongest, and is the most available to generate convective updrafts. Based on the relation of these two circulations, R88 proposed three states: 1) the “optimal” state, when the two circulations are in near balance, and the GUF is very vertical lifting; 2) the “less than optimal shear” state, when the circulation of the cold pool is too strong to balance the ambient wind shear. Then the surface outflow of the cold pool is intensified, and the updraft is weakened and becomes more rearward slanted above the cold pool; 3) the “greater than optimal shear” state. At this state, the circulation of the cold pool is weaker than that of the ambient wind shear. The updraft slants forward, and consequently produces a “rain curtain” ahead of the surface gust front, which will cool and slow down the moist warm airflow into the storm.

FO88 and L98 proposed that, when the multicell storm is at the “optimal” state, the GUF and the surface outflow could be intensified. This makes the surface gust front move faster than the basic wind. As a result, the upper portion of the GUF slants rearward above the cold pool, and it will be cut off into a new individual cell by the strong compensative downdraft to its near east. This new cell then propagates to the rear and further develops into a next mature convective cell with the help of the upstream warm moist inflow. Meanwhile, the cold pool is restrengthened by rainfall produced by the new mature cell, and the GUF is reintensified to regenerate another new convective cell. Then the first new cell is cut off the incident upstream warm moist flow and is replaced by the second new cell. Consequently, the first cell decays and dissipates, while the second cell continues developing into a new mature convective cell. With this repetitive process, new convective cells regenerate, develop, and substitute, and then the multicell storm could maintain for a long time. In one word, the new cell regeneration at the “optimal” state is an important mechanism for the development and maintenance of the multicell storm.

Different from L98, FO88 found another by-product of the new cell regeneration, a “secondary cell”, which is triggered during the time between two successively regenerated cells split from the GUF. The “secondary cell” is located in the middle of the mature cell and GUF (see Fig. 7 in FO88). Since the “secondary cell” is quickly cut off the warm moist airflow by the follow-up new cell from GUF, it would soon be replaced, and never be a mature cell. However, the transient process of the by-product was not elucidated in FO88. In addition, FT98 found a strong unstable zone that existed a few kilometers upstream of the GUF, where there were intense perturbations that could drift toward the storm, and join into the low-level inflow to become a “convective trigger”. This may cause a sudden enhancement of the GUF and birth of a new cell. Obviously, the unstable perturbation zone presented in FT98 is located ahead of, but not within the multicell storm. Could this perturbation be produced within the storm, and develop into a new mature convective cell or not? This
is the topic of this paper.

The paper is structured as follows: Section 2 describes the model setup, initial condition, and experimental design. Section 3 presents the results and discussion of numerical simulations. Conclusions are given in Section 4.

2. Model description and experimental design

2.1 Model description

The numerical model used in this paper is the Advanced Regional Prediction System (ARPS) developed by Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma (Xue et al., 2000, 2001). The computational domain is two-dimensional in this study, and the domain grid points are 403 in x and 53 in z direction, respectively. Arakawa C grid is adopted in the horizontal coordinate with a resolution of 1 km. In the vertical direction, a terrain-following stretched coordinate is utilized with a resolution varying from 100 m at low levels to 500 m at upper levels. The model physical domain is 16 km from the surface, and a sponge layer with Rayleigh friction is imposed above the physical domain from 16 to 25 km. The model periodically opens the eastern and western lateral boundaries to allow disturbances to pass through. The lower boundary is assumed rigid, free-slip flat. A fourth-order computational mixing scheme is used in the horizontal and vertical momentum advection, and the horizontal and vertical scalar advecting are, respectively, fourth and second order, and their computational mixing coefficient is set to 5.0\times 10^{-5} \text{ s}^{-1}. The 1.5-order TKE, subgrid scale turbulence scheme, and Kessler warm rain microphysics parameterization (Kessler, 1969) are used in the simulations. The Coriolis force, surface drag, radiation physics, and surface physical parameterization are neglected. The time step is 5 s, and the simulation is output every 2 min.

2.2 Initial condition

The temperature and moisture profiles of the initial condition are the analytic one designed by Weisman and Klemp (1982), which reflects a conditionally unstable sounding typical of mid-latitude multicellular storms.

\[
\begin{align*}
\theta(z) &= \theta_0 + (\theta_{tr} - \theta_0)\left(\frac{z}{z_{tr}}\right)^{1.25}, & z \leq z_{tr}; \\
\text{RH}(z) &= 1.0 - 0.75\left(\frac{z}{z_{tr}}\right)^{1.25}, & z \leq z_{tr}; \\
\theta(z) &= \theta_{tr}\exp\left[\frac{g}{c_p}\frac{\theta_{tr}}{L_{tr}}(z - z_{tr})\right], & z \geq z_{tr}; \\
\text{RH}(z) &= 0.25, & z \geq z_{tr}.
\end{align*}
\]

Here, the height of tropopause \( z_{tr} \) is 12 km, the tropopause potential temperature \( \theta_{tr} \) is 347 K, and the ground surface potential temperature \( \theta_0 \) is 300 K. A well-mixed boundary layer is used at lower levels from surface to 1200-m height with a mixing ratio of 0.015 kg kg\(^{-1}\). The value of the convective available potential energy (CAPE) is kept a constant of 2600 J kg\(^{-1}\), and the convective inhibition (CIN) is -29 J kg\(^{-1}\). The corresponding lifting condensation level (LCL) is 808 m, and the level of free convection (LFC) is 1377 m (Fig. 1). The initial disturbance is set up with a 2-K warm bubble at a horizontal radius of 5 km and a vertical radius of 1 km, located 125 km away from the western boundary and at a height of 1 km above the surface.

2.3 Experimental design

To test the capability of the numerical model to simulate the multicell storm presented by L98, a control experiment (CTRL) is designed. The background wind speed is assumed to linearly increase from 0 m s\(^{-1}\) at ground to 10 m s\(^{-1}\) at the height of 3000 m, and is kept a constant at 10 m s\(^{-1}\) above 3000 m (Fig. 2).

Weisman et al. (1988) used a two-dimensional model to simulate the super-cell storm and found that the simulated storm would evolve through three phases: (1) "initial phase", at this stage the convection is created by the initial forced disturbance; (2) "periodically redeveloping phase", during this stage, the storm updraft alternately oscillates between system-relative vertical and downshear tilted orientations with height; (3) "surging out phase", as the evolution of the storm continues, the system-relative upshear tilting updraft occurs. Accompanying this, when the cold pool becomes stronger, the updraft above the cold pool slants more rearward which can influence the lifting of the unsaturated airflow to LCL or LFC.
Fig. 1. A skew $t$-$T$ plot of the initial sounding used in the simulations (from Weisman and Klemp, 1982).

Actually, the “surging out phase” is equivalent to the “less than optimal shear” state proposed by R88. In order to further study the mechanisms of new cell regeneration and development at the “less than optimal shear” state, by referring to the wind profile in Bryan et al. (2007), the environmental wind profile for three different sensitive experiments are shown in Table 1 and Fig. 2. In experiment MS1, wind speed linearly decreases from 3 m s$^{-1}$ at ground to 1.67 m s$^{-1}$ at the height of 500 m, and above 500 m it is set to be the same as in CTRL. In experiment MS2, wind speed linearly decreases from 6 m s$^{-1}$ at ground to 1.67 m s$^{-1}$ at the height of 500 m, and above 500 m it is set to be the same as in CTRL. In experiment MS3, wind speed linearly decreases from 6 m s$^{-1}$ at ground to 3.33 m s$^{-1}$ at the height of 1000 m, and above 1000 m it is set to be the same as in CTRL, which keeps the same decreasing rate of lower-level upshear as that in MS1.

### Table 1. Experimental design

<table>
<thead>
<tr>
<th>Cases</th>
<th>Height (m)</th>
<th>Ambient wind (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>0–3000</td>
<td>0–10</td>
</tr>
<tr>
<td>MS1</td>
<td>0–500</td>
<td>3–1.67</td>
</tr>
<tr>
<td>MS2</td>
<td>500–3000</td>
<td>1.67–10</td>
</tr>
<tr>
<td>MS3</td>
<td>0–1000</td>
<td>6–3.33</td>
</tr>
<tr>
<td></td>
<td>1000–3000</td>
<td>3.33–10</td>
</tr>
</tbody>
</table>

Note: the ambient wind is 10 m s$^{-1}$ above 3000 m in all cases.

3. Experimental results and discussion

#### 3.1 Control experiment

In CTRL, after the model is initiated, an updraft is forced up by the initial warm bubble.
Fig. 2. The initial wind profile used in the simulations. The solid line is for CTRL, the thin dashed line for MS1, the dotted line for MS2, and the thick dashed line for MS3.

40 min, evaporation of hydrometeors fell to surface induces a cold pool. The cold pool can spread out to east and west axisymmetrically. At both the eastern and western leading edges of the cold pool, GFU is forced by the strong convergence between the cold pool and the ambient wind. The updraft at the eastern edge is stronger and more persistent than that at the western edge. Because, in the vicinity of the eastern edge, the circulation associated with the cold pool and that with the ambient wind shear are near equal but of opposite signs, which results in a more vertically oriented updraft lifting more warm and moist air to release the CAPE. Nevertheless, in the vicinity of the western edge, the circulations are both positive, making the updraft more slanted and horizontal along the upper edge of the cold pool, unfavorable for triggering a strong convective cell. Afterwards, the eastern updraft commences to oscillate between the vertical and downshear-tilted orientations. Until by 180 min, new cells begin to be periodically split from the GFU. Figure 3 illustrates the four evolution stages of the convective cells from $t = 220$ min, which are, respectively, initiation, development, mature, and dissipation from front to rear. Owing to the strong outflow of the cold pool, the surface gust front propagates faster than the upper portion of GFU, which induces the upper portion of GFU to rearward slant above the cold pool. At $t = 226$ min, two convective centers appear in the GFU. Then an individual cell (Cell A in Fig. 3) is split from the GFU by 230 min, which would develop into a mature cell and replace the old mature cell. So far, one cycle of the new cell regeneration has been completed, with a period of about 10 min. Therefore, dependent on this repetitive process of new cell generation at the “optimal” state, the multicell storm maintains and lasts for a long time. It is reasonable to say that the model used in this study has reproduced the simulation presented in L98.

3.2 Sensitivity experiments

In the sensitivity experiment MS1, after adding an upshear in the ground layer (0–500 m) to the wind profile in CTRL (see Fig. 2), the cold pool outflow strengthens and the eastern propagation of the cold pool is accelerated. Figure 4 shows the distribution of vertical velocity for a subdomain ($260 \leq x \leq 360$ km) in MS1. During a complete circle ($194$–$208$ min), the maximum vertical velocity of the eastern updraft is about $3.4$ m s$^{-1}$, which has been significantly weakened compared with that of $5.6$ m s$^{-1}$ in CTRL. The reason for such a difference is that in MS1 the original balance between the two circulations associated respectively with the cold pool and the ambient wind shear breaks down due to the lower-level upshear, and the storm state transfers from the “optimal” to the “less than optimal shear” state. In addition, in MS1, a new episode appears in the new cell regeneration. At $t = 198$ min, a small disturbance located at $x = 298$ km develops into a separate individual convective cell (Cell B in Fig. 4). Meanwhile, a new cell (Cell A) at $x = 308$ m is being split from the GFU. After that, Cell B well grows, while Cell A develops slowly, and finally merges into Cell B at $t = 208$ min. Actually, Cell B is surprisingly similar to the “secondary cell” proposed in FO88, with the only difference being that Cell B has developed into mature convection and replaced the old mature cell in this study. However, this episode disappears during the time from 214 to 226 min, and another new cell from the GFU becomes the next mature convection. In summary, the upshear in the ground layer will enhance the cold pool outflow, and undermines the quasi-balance of the circulations related to the cold pool and the ambient wind shear, which renders the system from the “optimal” to the
Fig. 3. Vertical velocity (interval of 2 m s\(^{-1}\); shaded \(w \geq 1\) m s\(^{-1}\)) for a subdomain (260 km \(\leq x \leq 360\) km) in the CTRL simulation. The density current is represented by the \(-1\)-K potential temperature contour (low-level dashed line). "A" denotes the new convective cell at the "optimal" state.
Fig. 4. As in Fig. 3, but for MS1. “B” denotes the new convective cell at the “less than optimal shear” state.
Fig. 5. As in Fig. 3, but for MS2. "B" and "B2" denote new convective cells at the "less than optimal shear" state.
“less than optimal shear” state. Moreover, at this state the new cells are generated not only from the GFU, but also from the strong vertical disturbance ahead of the mature convection, and the latter could also develop into a next mature convective cell.

Compared with MS1, the depth of the upshear layer is kept the same but the surface wind speed is increased to 6 m s\(^{-1}\) in MS2, which leads to a different cycle of new cell regeneration and development. As described in Fig. 5, the increase of the surface wind speed further hastens the cold pool outflow, and completely breaks down the balance between the circulations associated with the cold pool and the ambient wind shear. The storm has ultimately shifted to the “less than optimal shear” state. In CTRL (Fig. 6a), warm and moist air in the upstream area is drawn into the stronger GFU, while Fig. 6b shows that the GFU in MS2 could not attain the great degree of development, and the upstream warm and moist air flows over the GFU. Nonetheless, the GFU is still a beneficial and indispensable factor for the development of new cells because it lifts the upstream unsaturated air to saturation level along the upper edge of the cold pool. Moreover, the ground gust front in MS2 lies further away from the center of the maximum vertical velocity within the multicell storm than that in CTRL or MS1, which provides sufficient room for the disturbance ahead of the mature convection to trigger a new cell. At \(t = 218\) min, a new cell (Cell B in Fig. 5) appears at \(x = 334\) km ahead of the mature convection (at \(x = 320\) km). With the upstream (east) warm and moist air flowing in, this new cell develops into a next mature convective cell (\(x = 325\) km at \(t = 224\) min) and replaces the old mature cell at \(t = 230\) min. At the same time, to the eastern side of the new cell there appears another new cell (Cell B2), and no cell separates from the GFU. Thereby, MS2 has illustrated another conceptual model of new cell regeneration and development, in which the cell is triggered in the strong vertical disturbance ahead of the mature convection, and then develops into the next mature convective cell.

Figure 7 has magnified the vertical velocity in the subdomain (318 \(\leq x \leq 355\) km, 0 \(\leq x \leq 6\) km) displayed in Fig. 5. During 217–221 min, the compensative downdraft (near \(x = 330\) km) upstream of the mature convection is enhanced, with its maximum value being increased by 2 m s\(^{-1}\). Meanwhile, to the east, the compensative updraft (at \(x = 334\) km) has also increased by 2 m s\(^{-1}\), and has produced a new cell (Cell B).

As shown in Fig. 7, Cell B is produced by the

![Figure 6](image_url)

**Fig. 6.** Vertical velocity (black line; interval of 2 m s\(^{-1}\); shaded for \(w \geq 1\) m s\(^{-1}\)) and perturbation water vapor specific humidity deviated from the initial state (gray line; interval of 0.5 g kg\(^{-1}\)) for (a) CTRL (\(t = 228\) min; 290 km \(\leq x \leq 350\) km; 0 \(\leq z \leq 10\) km) and (b) MS2 (\(t = 224\) min; 320 km \(\leq x \leq 380\) km, 0 \(\leq z \leq 10\) km). The bold gray line denotes 0 g kg\(^{-1}\), and the low-level dashed line denotes the density current.
Fig. 7. Vertical velocity for a square subdomain (318 km ≤ x ≤ 355 km, 0 ≤ z ≤ 6 km; see the dashed box in Fig. 5b) in MS2. Black solid lines represent positive values, gray solid lines denote zero value, and dotted lines represent negative values. The contour interval is 1 m s⁻¹.
disturbance ahead of the mature convection. The process could be as following: during 217–221 min, the compensative downdraft (at $x = 330$ km) to the west of the new cell enhances by 2 m s$^{-1}$. While, at the eastern side, the compensative downdraft (at $x = 338$ km) experiences almost no change, and a weak intensification later appears following the updraft enhancement of Cell B at $t = 221$ min. Furthermore, the GFU also undergoes nearly no enhancement. This process of new cell regeneration is surprisingly similar to that in FT98, but the only difference is that the disturbance in FT98 is situated upstream (ahead) of the GFU, while in this study it exists between the ground gust front and the center of the maximum vertical velocity within the storm.

In order to further validate this new mechanism for the new cell regeneration, another sensitivity experiment MS3 is carried out by keeping the same surface wind speed as MS2, but increasing the upshear layer from surface to 1000-m height. The gross features in MS3 are very similar to that in MS2. Therefore, it implies that the surface wind is a more important factor to transfer the storm from the “optimal” to the “less than optimal shear” state.

### 3.3 Discussion

As presented above, there are two different mechanisms of new cell regeneration, respectively. One is related to the “optimal” state in CTRL, and the other the “less than optimal shear” state in MS2. In CTRL, the new cell regeneration is consistent with that in L98. The new cell separates from the deeper lifting and rearward slanting GFU, while in MS2, the new cell is produced by the strong disturbance ahead of the mature convection. The reason for such a difference is a ground-layer upshear prescribed in MS2, which can bring on two significant influences: 1) it breaks down the balance of the two circulations associated with the cold pool and the ambient wind shear, suppresses the development of GFU, and finally transforms the storm from the “optimal” to the “less than optimal shear” state; 2) it enhances the cold pool outflow, hastens the surface gust front propagation, and lengthens the horizontal distance between the ground gust front and the center of the maximum vertical velocity within the multicell storm, all of which would provide a sufficient condition for the well development of the new cell at the “less than optimal shear” state. Figure 8 shows this horizontal distance during 190–250 min. In all the experiments the distance exhibits a periodic oscillation. The horizontal distance is about 30.0 km in MS2, much longer than that in CTRL (about 17.0 km). While it is about 25 km in MS1, larger than that in CTRL, and less than that in MS2. It has a rapid
reduction from 34.0 km at $t = 222$ min to 16.0 km at $t = 224$ min, which has also proved that the storm is transferring from the "less than optimal shear" to the "optimal" state. MS1 seems to display a transitional

Fig. 9. Time-space plot of vertical velocity ($u > 0.5$ m s$^{-1}$; contour interval 1 m s$^{-1}$) at $z = 2.5$ km for (a) CTRL, (b) MS1, (c) MS2, and (d) MS3 in the frame of reference with the gust front.
feature between CTRL and MS2. The two mechanisms can alternately operate in MS1. In MS3, the averaged horizontal distance is 29.5 km, which is equivalent to that in MS2. It implies that the ground wind is a dominant factor to manipulate the outflow strength of the cold pool.

Figure 9 illustrates a time-space plot of vertical velocity at z = 2.5 km for CTRL, MS1, MS2, and MS3 in the frame of reference with the surface gust front. As shown in Fig. 9, the GFU is permanently located at the eastern edge of the cold pool, and there are new cells periodically generated in each experiment. Obviously, the new cells in CTRL are separated from GFU and propagate toward the rear, as is under the mechanism at the “optimal” state. While the new cells in MS2 are not produced from GFU but triggered ahead of the mature convection, and the GFU is much weaker than that in CTRL, as is under another mechanism at the “less than optimal shear” state. Transitionally, the new cell regeneration in MS1 becomes complicated, as these two mechanisms alternately operate: during 200–210 min, the GFU is very weak, and the new cell is triggered ahead of the mature convection; during the following time period, the new cell is produced from the restrengthening GFU. This transitional feature of MS1 explains why the horizontal distance between the ground gust front and the center of the maximum vertical velocity within the multicell storm in MS1 is in the middle of these in CTRL and MS2, and why it has a rapid reduction at t = 223 min.

As seen in Fig. 9, the updraft of the new cell in CTRL is stronger than that in MS1 and MS2, which is controlled essentially by the two different mechanisms: 1) at the “optimal” state in CTRL, the GFU is rather vertical so full CAPE held in the upstream inflow is immediately released, and penetrative convection is produced. However, the updraft in MS2 is weaker and highly slanted than that in CTRL; 2) the horizontal distance between the ground gust front and the center of the maximum vertical velocity in CTRL is shorter than that in MS2, which draws more warm and moist air into the convection. In MS1, the convection at the “less than optimal shear” state (200–215 min) is weaker than that at the “optimal” state (215–230 min).

Keeping the same decreasing rate of upshear but doubling the depth of the upshear layer and the surface wind speed, the simulated results in MS3 are very similar to those in MS2. However, the increased height of the upshear layer reduces the negative circulation of the ambient wind shear, which leads the storm into a state closer to the “optimal”. As a result, the convection in MS3 becomes a little stronger than that in MS2.

Two conceptual models for these two mechanisms are given in Fig. 10. Figure 10a shows the mechanism at the “optimal” state similar to that of L98, in which the new cell (Cell A2) is split from the strong GFU and propagates toward the rear, and then it replaces the mature convection (Cell A1). Another mechanism at the “less than optimal shear” state is described in Fig. 10b, in which the new cell (Cell B) is produced by the vertical disturbance ahead of the mature convection, and then it develops into the next mature convection. In the second model, the GFU is weakened, but it is still a beneficial and indispensable factor for the development of new cells by lifting the upstream unsaturated air to the saturation level along the upper edge of the cold pool.

4. Conclusions

The ARPS model is used to study the mechanisms of new cell regeneration and development within a multicell storm. When only a downshear exists at low levels, a cold pool is created by the evaporation of the surface rainfall, and at the eastern edge of the cold pool a strong gust front is produced by wind convergence. Owing to the upstream inflow, the GFU could develop into a deep lifting and its upper portion would slant rearward above the cold pool since the gust front propagates faster than the basic wind. Then the compensative downdraft cuts off the upper portion of the GFU, and a new cell forms and propagates to the rear. After well development, the new cell replaces the old mature convective cell to be the next mature convective cell. Actually, this mechanism of new cell regeneration, development, and substitution is the
Fig. 10. Schematic models for the cell regeneration and development within a two-dimensional multicell thunderstorm at (a) the "optimal" state and (b) the "less than optimal shear" state proposed in this paper. "A1", "A2", and "B" denote new convective cells.

However, when a ground-layer upshear is added to the basic wind field, the surface outflow of the cold pool is enhanced, and it breaks down the balance of the two circulations associated the cold pool and the ambient wind shear. This makes the storm transfer from the "optimal" to the "less than optimal shear" state, and the horizontal distance between the ground gust front and the center of the maximum vertical velocity is increased. As a result, the new cell is not split from the GFU but produced by the disturbance ahead of the mature convection. It is very similar to the "secondary cell" proposed by FO88, but the new cell in this study can well develop and replace the old mature convection to be a next mature cell. Obviously, it is a new mechanism at the "less than optimal shear" state, different from that at the "optimal" state.

Of course, the new mechanism presented in this paper is not a contradiction to that proposed by L98. With the ground wind speed at a certain strength, these two mechanisms can alternately operate within the multicell storm. When the ground wind speed is strong, the new cell is produced ahead of the mature convection; when it is weak, the new cell is separated from the GFU. Therefore, the mechanism proposed by the present study is a complementary to the previous
mechanism of L98 for the storm development. The multicell storm can continue to develop and last for a long time in spite of being at the “less than optimal shear” state.

REFERENCES