Three-Dimensional Numerical Modeling of Convection Produced by Interacting Thunderstorm Outflows.  
Part II: Variations in Vertical Wind Shear

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ABSTRACT

In this second paper in a series on outflow interactions, we use the three-dimensional model described in Part I to examine the effects of vertical wind shear variations on cloud development along intersecting thunderstorm outflow boundaries. Three wind shear profiles are used in this study; shear only above cloud base, shear only below cloud base, and shear both above and below cloud base. As in Part I, the shear is unidirectional and is oriented perpendicular to the line containing the two initial outflow-producing clouds (which are spaced 16 km apart). Using the environmental thermodynamic structure from the control simulation in Part I, we vary the shear magnitude in each profile and examine the properties of cloud development in the region where the two outflows collide (the outflow collision line or CL).

The model results show that the intensity and the time interval between successive cell updraft maxima of the first two clouds along the CL (both of which are triggered by the outflow collision) are controlled by the strength of the vertical wind shear. In strong shears, the upshear member of this pair of clouds has a head start in development, and becomes the stronger cell of the two. The timing difference between these two clouds is a few minutes. In weaker shears, the two clouds grow at nearly the same rate, and therefore have similar intensities and a smaller timing difference. The presence of wind shear in the boundary layer is found to enhance the updrafts of these two cells in all cases.

The strength of the third and subsequent clouds which form along the CL is related to the speed at which the gust front moves away from the developing cells. The larger this separation speed, the more quickly the gust front-induced convergence is removed from the clouds, and thus the weaker they are. The third and subsequent cells along the CL are found to be more intense when shear is present in the cloud-bearing layer. The factors governing the timing difference of the third and successive cells to form along the outflow's leading edge are not clear at this time.

1. Introduction

In Part I of this series (Droegemeier and Wilhelmson, 1985), we used the Klemp and Wilhelmson (1978) three-dimensional numerical cloud model to examine in detail how clouds are triggered in the region where two thunderstorm outflows collide. In addition, we discussed the sensitivity of these clouds to changes in low-level moisture.

In the current paper, we use the model described in Part I to examine the sensitivity of clouds forming along outflow collision lines (CL) to changes in the vertical wind shear. Vertical shear of the horizontal wind has long been recognized as an important parameter in the theory of convection (e.g., Newton and Newton, 1959; Asai, 1964, 1970a,b, 1971; Pastuskiov, 1975). Modeling studies have also stressed the importance of wind shear in the life cycle of convection (e.g., Takeda, 1971; Klemp and Wilhelmson, 1978; Thorpe, Miller, and Moncrieff, 1982) as well as in determining what mode of convection will form (Weisman and Klemp, 1982). One would therefore expect the wind shear to play an important role in determining the characteristics of clouds forming along outflow collision lines.

In this study, we vary the magnitude of the wind shear from weak to strong values in two physically distinct regimes: the outflow or subcloud layer (0–1 km), and the cloud-bearing layer (1–9 km). Since the cloud base height and outflow depth are similar in our experiments, we define three types of constant wind shear profiles:

- **SAn**: Shear only above cloud base;
- **SBN**: Shear only below cloud base;
- **SABn**: Shear above and below cloud base.

Here, $n$ is a number associated with each simulation, and a larger $n$ implies a weaker shear.

Figure 1 shows the model wind profiles as a function of height, and Table 1 lists the numerical values of the constant vertical wind shears for each experiment. The wind shears in this study are unidirectional and are oriented perpendicular to the line containing the two initial outflow-producing clouds (see Part I for details of the model configuration). As in Part I, the simulation

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using wind profile SA1 is designated the control experiment. Bulk Richardson numbers for the thermodynamic and wind profiles computed using Weisman and Klemp's (1982) method lie mainly within the range designated for multicell storms (100–1000; see Droegemeier, 1982).

2. The extreme cases

From both physical and dynamical viewpoints, the simplest setting for an outflow collision is a calm environment (though perfectly calm environments are never found in nature). In this extreme situation, the absence of vertical wind shear simplifies the interpretation of the many processes taking place during an outflow collision. Conversely, at the other end of the wind shear spectrum where the shear is large (e.g., the control simulation), several processes occur simultaneously (Droegemeier and Wilhelmson, 1985), making interpretation of the results more difficult. Thus, in order to examine the behavior of CL clouds during the transition from weak to strong shears, we present results from a no-wind simulation, a weak shear simulation (shear profile SA7 in Fig. 1a), and a strong shear simulation (the control case SA1). Keep in mind that the

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**FIG. 1.** Model initial wind profiles in meters per second as a function of height for the three wind shear profiles: (a) wind shear only above cloud base, (b) wind shear only below cloud base, and (c) wind shear above and below cloud base. Profile 1 in panel a is the control simulation.
TABLE 1. Model initial vertical wind profiles.

<table>
<thead>
<tr>
<th>Experiment*</th>
<th>$d\theta/dz$ (m s$^{-1}$ km$^{-1}$)</th>
<th>Percent of control simulation shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smx1</td>
<td>2.9</td>
<td>100</td>
</tr>
<tr>
<td>Smx2</td>
<td>2.4</td>
<td>83</td>
</tr>
<tr>
<td>Smx3</td>
<td>2.1</td>
<td>72</td>
</tr>
<tr>
<td>Smx4</td>
<td>1.8</td>
<td>62</td>
</tr>
<tr>
<td>Smx5</td>
<td>1.5</td>
<td>52</td>
</tr>
<tr>
<td>SA6</td>
<td>0.8</td>
<td>28</td>
</tr>
<tr>
<td>SA7</td>
<td>0.3</td>
<td>10</td>
</tr>
</tbody>
</table>

* $nn = A$ for shear only above cloud base; $nn = B$ for shear only below cloud base; $nn = AB$ for shear above and below cloud base; SA1 is the control simulation.

wind shear in these experiments is confined to the region above cloud base.

Figure 2 shows a series of vertical cross sections along the outflow CL of vertical velocity $w$ (m s$^{-1}$) and potential temperature perturbation $\theta$ (K), along with time series plots of the maximum rainwater mixing ratio $q_r$ (g kg$^{-1}$) for these three experiments.

In the no-wind simulation, two symmetric updrafts form (one at either end of the outflow) as the two outflows collide (Fig. 2a). One might imagine that the forcing due to the collision of the two nearly circular outflows would trigger a single cloud at the initial point of collision (as shown by the bold arrow in Fig. 2). However, as discussed in Part I, an updraft couplet forms as shown in the figure.

Twenty minutes after the outflow collision has occurred in the no-wind simulation (Fig. 2b), the two initial updrafts are developing into strong (albeit narrow) clouds. These two identical cells, denoted CL1 and CL2, both reach their peak intensity ~24 min after the outflow collision. As these two cells are growing, the outflow moves away from the updrafts and supports only weak lifting along each gust front (the leading edge of the outflow). Eventually, two new cells, CL3 and CL4, form simultaneously at the gust fronts. They are somewhat weaker than the first pair, and reach their peak intensity ~16 min later. We define this interval of time between successive cells as the cell timing difference. Both pairs of cells remain stationary, and do not move along with the gust front. They behave much like buoyant thermals which rise vertically upon initiation by the advancing gust fronts.

If we now introduce a small amount of constant vertical wind shear (0.3 m s$^{-1}$ km$^{-1}$) in the ambient environment above cloud base only (profile SA7 in Fig. 1a), the structure of the vertical velocity field induced by the outflow collision becomes asymmetric. Ten minutes after the outflows collide (Fig. 2d), the vertical wind shear has clearly altered the lifting due to the outflow collision such that the maximum anomaly in $w$ occurs above the center of the outflow. As seen in the figure, the first cloud CL1 develops in this region while the second cloud, CL2, which reaches its maximum vertical velocity ~5 min after CL1, forms to the south of CL1 (downshear). As in the control simulation SA1 discussed in Part I, cells CL1 and CL2 are triggered mainly by the forced uplifting due to the outflow collision. This accounts for the small timing difference between their updraft maxima. A third cloud eventually forms to the south of CL2, and reaches its peak intensity ~15 min after CL2. Therefore, in agreement with the findings for the control experiment in Part I, the large lapse of time between CL2 and CL3 suggests that CL3 (and all subsequent cells along the CL) is initiated by the convergence of air along the advancing outflow, and is not directly affected by the outflow collision.

If we now increase the wind shear above cloud base by an order of magnitude (the control case SA1 where $d\theta/dz = 2.9$ m s$^{-1}$/km; Fig. 2g, h), the updraft structure along the CL changes further. As seen in Fig. 2g, the maximum updraft region 10 minutes after the outflow collision is on the downshear side of the outflow (which is the region of strongest ambient low-level, outflow-relative flow). The first cell CL1 forms in this region, and is quickly followed (~5 min later) by CL2 (Fig. 2h). Note how mixing due to the strong vertical wind shear acts to broaden the updrafts compared to the weak shear and no-wind simulations. As in the weak shear case, a third cell is triggered downshear from previous ones, and reaches its maximum updraft strength some 15 min after CL2. Due to only weak lifting at the northern gust front in this simulation, no deep clouds are ever triggered there.

Examining the time series plots of $q_r$, the no-wind simulation shows that the two pairs of CL cells produce approximately the same amount of rain (Fig. 2c). However, when a small amount of wind shear is introduced above cloud base (Fig. 2f), the second cell’s rain value drops by ~50% (note that CL2 is obscured by CL1 in the low shear $q_r$ plot). Turpeinen (1982) also noted a bias toward larger updraft intensity for the upshear member of a pair of modeled cells in this type of experimental configuration. In the control experiment (Fig. 2i), CL2 produces less rain than in the no-shear case, but the third collision line cell is very intense ($q_r$ max = 16.5 g kg$^{-1}$). These results agree with those in Part I, where we found that wind shear above cloud base causes CL1s downdraft to tilt into the region occupied by CL2, thereby suppressing CL2s development. In contrast, CL3 forms well away from neighboring clouds, and is therefore not affected by tilted downdrafts to the north. Note that since CL2 is suppressed by CL1, the downdraft of CL2 is correspondingly weaker and exhibits less tilting than that of CL1.

3. Cloud properties in varying shear

In this section we discuss the sensitivity of the control simulation SA1 to changes in both the magnitude and profile of the vertical wind shear. All other model pa-
rameters (except for the domain speed) are the same in each experiment. The three wind shear profiles, discussed in section 1, are shown in Fig. 1.

a. Average characteristics of the CL clouds

Early in this research we focused our attention on the variations of cell behavior within each set of simulations (e.g., wind shear only below cloud base), looking for features such as cell strength and timing difference that could be related to the magnitude of the wind shear. However, individual clouds in some simulations did not behave as the trends suggested they would. Thus, despite the large variations in wind shear magnitude in each shear profile, details of cell behavior were not always predictable (Droegemeier, 1982). In part, the predictability and character of the modeled clouds were found to be sensitive to the proximity of the clouds to the open lateral boundaries (see Appendix). To minimize the effects of this sensitivity on cell behavior, we chose the domain speeds carefully so that the convection of interest remained as far away as possible from the lateral boundaries.

Given the variability described above, we decided that the most meaningful comparisons would be obtained by examining mean cloud properties for each
of the three sets of simulations. Table 2 shows the shear-weighted maximum updraft statistics for each CL cell in the three wind shear categories, along with the results for the no-wind simulation. Experiments SA6 and SA7 are not included in the shear above cloud base averages (see Table 1).

Table 2 indicates that the strength of the initial cloud is weaker when shear is present above cloud base. This result is plausible since wind shear in the growth layer tends to inhibit updraft development. Furthermore, as discussed in Part I, the initial thermal perturbation is located at \( z = 1 \) km with a vertical radius of 0.5 km. Therefore, it is not greatly affected by shear below cloud base, and consequently the average intensities of the initial clouds in the SB experiments are not significantly different from those in the no wind simulation.

The average maximum updraft intensity of the first and second collision line cells (CL1 and CL2) does not vary greatly among the wind shear profiles (Table 2). However, on the average, the presence of shear below cloud base seems to enhance the intensities of CL1 and CL2 (recall that CL1 and CL2 in the no-wind experiment are identical). This updraft enhancement is likely a result of the increased ambient low-level, outflow-relative flow over the gust front when shear is present below cloud base. It is interesting that CL2 is always slightly weaker than CL1 in the three shear profiles. This is a result of the competition for air between CL1 and CL2, as well as the suppression of CL2 by the tilted downdraft of CL1 to the north when shear is present in the cloud layer (see Fig. 20b in Part I).

The relationships noted between the average updraft intensities of CL1 and CL2 do not occur for the third cell CL3. Table 2 clearly shows that the presence of wind shear above cloud base is now a major factor in promoting the formation of intense CL3 clouds. In fact, apart from the initial clouds, the CL3 cells in the SA and SAB simulations are even stronger than those in the no-wind case. The intensities of CL3 in the SB and no-wind cases are quite similar due to the lack of wind shear in the cloud-growth layer. This suggests that shear in the boundary layer does not have a significant effect on the intensity of CL3.

Based on these average updraft statistics, we may draw the following conclusions. First, the strength of the cloud triggered by the initial thermal impulse is weaker when shear is present in the cloud layer. Second, wind shear below cloud base enhances the intensity of the first and second collision line clouds (i.e., those triggered mainly by the forcing of the outflow collision), but not the third. Finally, the presence of shear above cloud base clearly encourages the development of intense CL3 clouds (those triggered by air that is forced to rise up and over the gust front).

These results are qualitatively similar to those of Weisman and Klemp (1982), who found that successive cells forming along the gust front in the “secondary storm” regime became stronger as the wind shear was increased (note that their wind shear was nonzero from the surface to 10 km).

b. Cell characteristics along the CL

While the average statistics presented in section 3a provide information on overall cell behavior, they tend to mask the physical differences within each set of simulations. In this section we discuss the physical processes governing the strength and timing difference of successive cells for simulations with shear both above and below cloud base. The arguments presented here are equally valid for the other shear profiles, but are more easily illustrated using the SAB simulations.

In Part I, as well as in this paper, we have discussed how the first two collision line cells CL1 and CL2 are triggered by the outflow collision, and how they compete for the same air since they are located only a few kilometers apart. We now show that the intensity and timing difference of these two clouds are a function of the vertical wind shear.

Table 3 lists the maximum updraft statistics and timing differences between successive updraft maxima for the five simulations with shear above and below cloud base. Three points immediately become evident: the intensity of CL1 decreases as the shear decreases; the intensity of CL2 increases as the shear decreases (though the trend is not as clear); and the timing difference between CL1 and CL2 decreases (i.e., the cells tend to form closer together in time) as the strength of the wind shear decreases.

Previously we mentioned that two updrafts are initiated whenever the two initial outflows collide. Strong shear favors the development of the upshear member of this pair (CL1) over the downshear member (CL2). Cell CL1 eventually develops an extensive downdraft which becomes tilted by the strong wind shear. This in turn interferes with the (slower) growth of CL2, and thus CL2 is weaker (Table 3). This “head start” of CL1 over CL2 is indicated by the 6–7 min timing differences shown in Table 3. When the shear is decreased, two

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**Table 2.** Shear-weighted maximum updraft statistics for the collision line cells in the three wind shear profiles. Also shown are the statistics for the no-wind simulation.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( w_{\text{max}} ) (m s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
</tr>
<tr>
<td>Shear above</td>
<td>36</td>
</tr>
<tr>
<td>Shear below</td>
<td>45</td>
</tr>
<tr>
<td>Shear above/below</td>
<td>34</td>
</tr>
<tr>
<td>No-wind*</td>
<td>49</td>
</tr>
</tbody>
</table>

* Cells CL1 and CL2 are the same, as well as CL3 and CL4 (CL4 not shown).
TABLE 3. Maximum updraft statistics along the CL for simulations with shear above and below cloud base. Also shown is the timing difference of maximum updraft strength (in min) between CL1 and CL2.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>CL1</th>
<th>CL2</th>
<th>Timing difference (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAB1</td>
<td>26</td>
<td>19</td>
<td>6</td>
</tr>
<tr>
<td>SAB2</td>
<td>26</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>SAB3</td>
<td>23</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>SAB4</td>
<td>18</td>
<td>21</td>
<td>3</td>
</tr>
<tr>
<td>SAB5</td>
<td>18</td>
<td>24</td>
<td>2</td>
</tr>
</tbody>
</table>

updrafts are still triggered by the outflow collision, but the shear-induced bias for CL1 weakens and the two cells tend to grow at the same rate (timing difference of ~2 to 3 min). The updraft strengths of these two clouds are still different, but are weaker than in the higher shear cases where a larger timing difference is clearly present. Note that in weaker shears, CL1 does not have a strong tilted downdraft capable of interfering with CL2. In fact, CL2 is stronger than CL1 in the weaker shear simulations SAB4 and SAB5 shown in Table 3.

Focusing on the third CL cloud CL3, recall that it is not influenced by the outflow collision, but is instead triggered by air forced to rise up and over the advancing outflow. Unlike cell CL2, CL3 is not affected by tilted downdrafts from previous clouds. Indeed, the simulation results show that neither the intensity nor the timing difference of CL3 is related in any simple way to the magnitude of the wind shear. However, the intensity of CL3 does seem to be related to the separation speed between it and the outflow, i.e., the speed at which the gust front outruns the cloud.

Table 4 lists the maximum intensities of the CL3 cells along with their separation speeds (average downshear gust front speed minus the average speed of CL3). This table shows that strong CL3 clouds tend to be correlated with small separation speeds (e.g., a 1.5 m s$^{-1}$ difference in separation speed between two simulations over a 30 min period produces a difference of ~3 km in cell location relative to the gust front). Given the fact that the ground-relative (see Fig. 1) outflow speed along the CL is virtually the same in all simulations (~10–12 m s$^{-1}$), and that the cells might be expected to move at approximately the speed of the mean wind in the cloud layer (which is larger for larger shears), one would expect the outflow to outrun the cells faster in cases of weaker shear. However, Table 4 shows that this hypothesis is not supported by the results. What we are able to state with certainty from Table 4 is that the larger the separation speed, the more quickly the cell is removed from the convergent forcing at the gust front, and thus the weaker the cell is. The factors governing the separation speed are not clear at this time.

One possible explanation for the lack of a clear trend in these results would be that the cell speeds are governed by some mean wind speed in the lower part of the model atmosphere, which would be similar for all shear profiles used. Coupled with a nearly constant outflow speed in all simulations, it would be very difficult to define a relationship between the separation speed and the wind shear.

c. Three shear profiles for the control simulation

To further document the impact of vertical wind shear on modeled cloud development, we now compare the results of the control simulation SA1 with the corresponding simulations SB1 and SAB1 which have the same shear magnitude but different shear profiles. It is sufficient to examine these three simulations in order to gain an appreciation of the trends of cloud development present in the other experiments.

Figure 3 shows time series plots of maximum $w$ along the CL for these three experiments. The CL cells are identified by appropriate symbols, while the strength of the initial cloud (in m s$^{-1}$) is indicated in parentheses for each simulation.

In all three simulations, three clouds form along the outflow collision line. The first CL cloud intensifies at nearly the same rate in all three experiments. The presence of shear below cloud base (SB1 and SAB1) causes the updraft of CL1 to peak slightly earlier than in SA1. It is interesting to note that the strongest CL1 cloud occurs in run SAB1, i.e., the addition of shear below cloud base in the control simulation increases the strength of CL1 by ~3 m s$^{-1}$. Although the increase in this particular example is not extremely large, it does agree with trends found in other simulations.

Turning to the second CL clouds, we see an example of the relation between the intensity of CL1 and CL2 discussed in section 3a. When shear is present in the cloud layer (e.g., simulations SA1 and SAB1), cell CL2 becomes stronger as cell CL1 becomes weaker. As expected, this is not the case in SB1 (with no shear in the cloud layer) where CL1 and CL2 are vertically erect.

TABLE 4. Maximum updraft intensity and separation speed for cell CL3 in the simulations with shear above and below cloud base.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$w_{max}$ CL3 (m s$^{-1}$)</th>
<th>Separation speed (m s$^{-1}$)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAB1</td>
<td>33</td>
<td>-1.3</td>
</tr>
<tr>
<td>SAB2</td>
<td>27</td>
<td>-2.7</td>
</tr>
<tr>
<td>SAB3</td>
<td>24</td>
<td>-2.1</td>
</tr>
<tr>
<td>SAB4</td>
<td>30</td>
<td>-1.4</td>
</tr>
<tr>
<td>SAB5</td>
<td>30</td>
<td>-1.2</td>
</tr>
</tbody>
</table>

* Average downshear gust front speed minus average speed of CL3.
Note also from Fig. 3 how closely spaced in time CL1 and CL2 are compared to CL3. This supports our interpretation that only CL1 and CL2 are influenced by the forcing of the outflow collision.

Finally, Fig. 3 indicates that the third cloud is the strongest of the three along the CL in simulations SA1 and SAB1. This is again a clear indication that shear above cloud base favors strong CL3 clouds. In all cases, the clouds reach their peak intensities and decay rather quickly, much like buoyant thermals triggered in a convectively unstable environment.

Figure 4 shows horizontal cross sections in the computational domain for simulations SB1 and SAB1. The same information for the entire physical domain in the control run SA1 is given in Fig. 11 of Part I. Several features common to these simulations and to others in their respective shear categories, but not shown here, are

1) Strong clouds always from along the outflow CL independent of the wind shear profile or strength.

2) Apart from the CL, no clouds ever form laterally (i.e., on the east side) of the initial cloud. Therefore, in the absence of the mirror image cloud and the associated outflow collision, no clouds would have formed along the lateral edges of the outflow.

3) New cells always form downshear from previous ones. This occurs because the strongest ambient low-level, outflow-relative flow is from the south, and thus new clouds always from at the southern gust front along the CL. The exception to this occurs in very weak shears where the ambient low-level, outflow-relative flow is comparable at both gust fronts, and thus clouds are triggered both at the upshear and downshear edges of the outflow.

4) The downshear outflow speed is nearly independent of the wind shear magnitude in each set of experiments.

Looking now at differences between these simulations, and at trends within each shear category, we see from Fig. 4a that the outflow is nearly circular when shear is absent in the cloud layer (resembling the simulated outflows in Thorpe and Miller, 1978). This is in contrast to the north–south elongated structure present in Fig. 4b and in the control experiment in Part I. As discussed in Part I, this elongation of the outflow is a result of tilted downdrafts and rain regions in simulations with shear in the cloud layer.

Turning to clouds south of the initial cloud, Figs. 4a–b show that when shear is present above cloud base, clouds tend to form in pairs (e.g., B-B' and C-C' in Fig. 4b) south of the initial cloud A. Due to subsidence warming at the gust front by the tilted downdraft of cell A, no clouds ever form directly south of A in cases with shear in the cloud layer (see Part I). In contrast, when shear is present only below cloud base, the downdraft of A is vertically erect. Thus, cells such as B and D in Fig. 4a are able to form in addition to pairs of cells as in SA1 and SAB1.

4. Discussion and summary

In this second paper in a series on outflow interactions, we used the Klemp–Wilhelmson three-dimensional numerical cloud model to investigate the sensitivity of clouds forming along intersecting thunderstorm outflow boundaries to the profile and strength of the vertical wind shear. Three shear profiles were used in this study: shear only above cloud base, shear only below cloud base, and shear both above and below cloud base. The model configuration was identical to that in Part I (Droegemeier and Wilhelmson, 1985), with the wind shear being unidirectional and oriented perpendicular to the line containing the two initial outflow-producing clouds (which were spaced 16 km apart).

Our results showed that the location and timing difference (the time between successive updraft maxima) of the first two clouds along the outflow collision line (which were triggered by the forced uplifting of the outflow collision) were a function of the vertical wind shear. When there was no wind in the ambient environment, two symmetric updrafts of equal intensity formed (one at either end of the outflow) as the outflows collided. Since these clouds were identical, the timing difference between their updraft maxima was zero.

As the wind shear in the cloud layer was gradually increased, the first two collision line cells began forming...
Fig. 4. Isochrones of surface outflow boundaries (solid lines show the zero degree perturbation isentrope, ground relative framework) every 5 min for simulations (a) SB1 and (b) SAB1. Also shown are the positions of the maxima in vertical velocity (i.e., cell locations) at 1.7 km above the ground at 5 min intervals. The time when the updraft first appears at 1.7 km is indicated in minutes beside the identifying cell letter (the prefix CL denotes a cell along the outflow collision line). The lines connecting the bold dots depict the paths taken by the cells, all of which move toward the south. The results are shown for the computational domain only. (The associated physical domain is obtained by reflecting each figure about the outflow collision line.)

at the downshear portion of the outflow. In addition, as the shear was increased, the upshear member of the pair of clouds became the stronger, thereby causing the timing difference between the first and second collision line cells to increase.

Further studies are needed to examine the sensitivity of cell “periodicity” (i.e., cell timing difference) to factors such as the microphysical parameterization. In cases of strong wind shear, the cloud characteristics appeared to be governed primarily by the dynamics, whereas in weaker shears, the microphysics plays an increasingly important role to which the model results are likely more sensitive.

In contrast to the first two clouds, the third one to form along the outflow collision line was not influenced by the outflow collision (indicated in part by the large timing difference between the second and third collision line cells compared to that between the first and second). Rather, it formed as unstable, ambient low-level air was forced to rise up and over the advancing gust front. Unlike the first two clouds, whose intensities were determined mainly by the vertical wind shear, the intensity of the third cloud was related to the speed at which the gust front moved away from it (the cell-gust front separation speed). Although the factors which govern this separation speed have not been identified,
we did find that the larger the separation speed between the gust front and the cloud, the more quickly the convergent forcing at the gust front was removed from the cell's updraft. Consequently, the cell was also weaker.

The factors governing cell timing difference for CL3 and subsequent cells along the outflow collision line are not as clear as for CL1 and CL2. We are therefore continuing to examine the problem of cell "periodicity."

The model results obtained by varying the profile and strength of the vertical wind shear are

1) The strength of the cloud triggered by the initial thermal impulse was weaker when shear was present above cloud base. The stronger the shear, the weaker the cloud.

2) The presence of wind shear below cloud base seemed to enhance the intensity of the first and second collision line clouds. In contrast, the third cloud, which was apparently not influenced by the outflow collision, was stronger when wind shear was present above cloud base.

3) The intensity of the first (second) collision line cloud decreased (increased) as the wind shear was decreased.

4) Strong clouds always formed along the outflow collision line independent of the profile or strength of the vertical wind shear. This was not true in experiments with a drier boundary layer (see Part I).

5) No clouds would have formed along the lateral edges of the outflow in the absence of the outflow collision.

6) All clouds along the outflow collision line formed downshear from previous clouds where the ambient low-level, outflow-relative flow was the strongest. The exception to this occurred in weak shears where the relative flow was similar at both the upshear and downshear gust fronts along the outflow collision line.

7) When wind shear was present above cloud base, the outflow boundary was elongated along the vertical-shear vector. In the absence of shear, the outflow was nearly circular in shape.

8) As mentioned in Part I, when shear was present in the cloud layer, the tilt of the initial cloud's rainy downdraft prevented new convection from developing directly south of it. Rather, cells tended to form in pairs. In the absence of shear in the cloud layer, cells formed directly south of the initial cloud, as well as in pairs.

This research represents a limited set of experiments which are meant to help lay the foundation for further work. The next logical step would be to examine different orientations of the vertical shear vector to the outflow collision line, as well as using more realistic two-dimensional wind profiles in the ambient environment (e.g., Wilhelmson and Chen, 1982). Further studies are also needed to fully understand the implications of low- and midlevel moisture variations on clouds triggered by colliding outflows.

In the third paper of this series (Wilhelmson and Droegemeier, 1986), we will use the cloud model to examine the effects of surface friction on outflow structure and modeled cloud development.

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APPENDIX

Lateral Boundary Effects

A practice commonly used in numerical cloud models to keep convection of interest away from the model lateral boundaries is the addition of a constant velocity to the base state wind field (i.e., a Galilean transformation, equivalent to moving the model domain at a constant velocity, which leaves unchanged the storm-relative winds). Despite the use of this technique and improvements in the formulation of open lateral boundary conditions (e.g., Orlanski, 1976; Oliger and Sundstrom, 1976) it is still important to ask the question "How close to an open lateral boundary can

![Figure A1](image-url)  
**Fig. A1.** Time series plots of maximum vertical velocity $w$ (m s$^{-1}$) along the outflow collision line for simulations A and B. The peak velocities associated with the collision line cells are also indicated.
a feature of interest go before it is 'significantly' affected by the boundary?"

In this Appendix we document lateral boundary effects by considering two simulations using wind shear profile SA2 shown in Fig. 1a. Simulation A is identical to SA2 presented in the text, while in simulation B, the model domain is intentionally moved too rapidly to the south. Thus, new clouds develop near the northern lateral boundary.

Figure A1 shows a time series plot of maximum updraft intensity along the outflow CL for simulations A and B. By 50 min, differences in cell development are
clearly evident, due primarily to a lag in time of cloud growth in simulation A. The second CL cells not only have significantly different intensities, but they also reach their peak intensity some 7 min apart. The difference in cell development is seen to be even more dramatic for CL3.

To further document the differences in cell evolution, Fig. A2 presents vertical cross sections along the outflow of vertical velocity and the outflow boundary (stippled). This figure clearly shows that significant changes in cell evolution due to boundary effects are taking place. Note the difference in location of the relative maxima in rainwater shown by the bold dots.

It is clear that undesirable changes in both the strength and progression of cloud development occur when clouds are near open lateral boundaries. In the simulations presented in the text, we tried to keep the convection near the center of the model domain. As a result, several simulations had to be run again using corrected domain speeds. The results from these corrected simulations further illustrated the lateral boundary effects documented in Figs. A1 and A2. In addition, they revealed that the boundary effects are more pronounced in weakly sheared environments.

REFERENCES


