Cell Merger Potential in Multicell Thunderstorms of Weakly Sheared Environments: Cell Separation Distance versus Planetary Boundary Layer Depth

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ABSTRACT

Using high-resolution three-dimensional numerical experiments, this paper shows that the cell separation distance scales as 0.75 times the planetary boundary layer (PBL) depth for successful cell mergers between constructively interacting cells within multicell thunderstorms. This boundary layer scaling is determined from several simulations of convective cell pairs with a fixed PBL depth and is shown to be valid for other sensitivity simulations with larger PBL depths. This research establishes a robust and quantitative relation between prestorm ambient conditions and cell merger potential useful for research efforts on the multifaceted cell merger process of multicell thunderstorms. The weakly sheared ambient prestorm conditions of the 9 August 1991 Convection and Precipitation/Electrification Experiment (CaPE) multicell thunderstorm are used to initialize the cell pair simulations.

Since ambient wind and wind shear are assumed to be zero, only simple cell mergers, defined in this study as those between cell updraft cores joined but not overlapping in the convective stage, are shown to be possible. The coarse-resolution simulations of Stalker suggest that ambient wind shear may be necessary for forced cell mergers, defined in this study as those in which the initial updraft cores are found apart. The scenarios of overlapping initial updraft cores for cell merger are considered physically invalid in this study.

1. Introduction

Cell merger is a complex and nonlinear dynamical–microphysical process in which two adjacent convective cells tend to merge into a single cell. Upon merging, the merged cloud entities may exhibit such characteristics as increased cloud diameters and cloud depths (e.g., Simpson and Woodley 1971; Changnon 1976; Wiggert et al. 1981; Woodley et al. 1982). More importantly, the merged cells may experience increased upward motion and may possibly produce augmented precipitation compared to either of the original interacting cells in isolation. This likelihood of augmented precipitation, upon cell merger, received a great deal of research attention in the past and continues to get the attention of individual atmospheric scientists and research agencies both from observational and numerical modeling standpoints. Particularly, research interest in the cell merger process exists because of possible opportunities to increase precipitation via cloud seeding. At the same time, other implications of cell merger may include damaging effects of severe thunderstorm phenomena such as strong surface winds, increased potential for lightning, etc. Despite the above-stated reasons for the research interests and numerous pioneering previous studies, a number of unknowns still remain. For example, existing cell and cell merger definitions are ad hoc in nature and thus allow for only qualitative descriptions of cell interactions and cell mergers. Limited computational resources of the past may have rendered previous numerical studies more idealized and less quantitative. While this study attempts to fill the void by developing quantitative descriptions of cell characteristics and cell mergers, a more penetrative development of the theory on the fluid dynamics of cell mergers is beyond the scope of this paper [e.g., see Rauscher (1953) for details].

Based on the vast volume of published research and from our own research experience on the cell merger process, two key aspects may be considered to stand out: (i) the quantification of the effects of various cell interactions on precipitation and (ii) the establishment of a connection between prestorm ambient conditions
AUGUST 2003 1679

STALKER AND KNUPP

and cell merger potential. The former aspect can significantly benefit research efforts to understand cell interactions responsible for precipitation augmentation via cloud seeding (e.g., Levy and Cotton 1984; Rosenfeld and Woodley 1989; Rosenfeld and Woodley 1993; Changnon et al. 1995; Czys et al. 1995). The latter aspect, for example, can potentially benefit the efforts to forecast the severity of multicell thunderstorms more accurately, based upon prestorm conditions typically shown in temperature, dewpoint temperature, and wind profiles. Other real-time observations of a characteristic cell separation distance, from such instruments as radars, satellites, etc., may be assimilated into any operational forecasting algorithms based on such known cell merger signatures for further improvements in forecast accuracy. Additionally, any relation between the prestorm conditions and the cell merger potential can also be used to build robust cell merger parameterizations for coarse-resolution atmospheric models. The latter aspect of finding a relation between prestorm conditions and cell merger potential is the focus of our research originally reported in Stalker (1997).

One of the many difficulties that a research investigator of the cell merger process faces is the lack of a clear and quantitative description of a cell merger itself (e.g., Westcott 1984, 1994). For example, a cell merger has been defined using upward motion or rainwater in previous studies. A further difficulty in using upward motion and rainwater variables together to describe cell mergers arises from a weakened correlation between the updraft and rainwater cores, especially beyond the mature stage during which cell mergers may typically occur (e.g., Stalker and Knupp 2002). Because of this latter difficulty, a cell merger must be depicted 1) using upward motion at higher elevations within the merged cell where relatively stronger upward motions tend to exist during the mature stage and 2) using rainwater at lower elevations where larger rainwater tends to accumulate at this advanced stage. In other words, it is not always possible to simultaneously show cell mergers using stronger upward motion and larger rainwater mixing ratios at any one level. Indeed, downward motions due to excessive water loading may exist within the interacting cells at lower elevations adjacent to the merged rainwater core. These disparate elevations at which to use the updraft and rainwater cores for fully depicting the cell merger process are an important aspect of our research. The authors of this paper have published a note on the above issue for objectively defining convective cells within multicell thunderstorms (Stalker and Knupp 2002).

The current study also finds it advantageous to define both simple and forced cell merger types as shown in Fig. 1. A simple cell merger is defined as one in which the upward motion cores within the interacting cells in the convective stage are initially joined without any overlap. In the case of a forced cell merger, the interacting cell cores neither join nor overlap. Cell merger between initially overlapping cell cores is not considered physically valid in this study. It is important to distinguish our definition of a cell core, a cloud region with stronger upward motion, from a traditionally defined interacting cell (or cell diameter) that indicates the diametrical distance between cloud edges or cloud–cloud–free interfaces (see Fig. 2b). It is also important to note that the cell core diameter is always smaller than the cell diameter by as much as 50%.

The broader goals of this study include the determination of a relation between the PBL depth \( Z \) and the cell separation distance \( D_s \) for a simple cell merger from six baseline high-resolution (100 m) numerical experiments (see Table 4). The definition of McNider and Kopp (1990), who related \( Z \) to a characteristic thermal perturbation length \( \lambda_m \) or to a characteristic cell (cloud) diameter, is used to initiate convective cell pairs in the cloud model. According to these authors’ similarity

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**Fig. 1.** Cell merger types defined for the current study: (a) a simple cell merger in which the cell separation distance is equal to the cell core diameter; (b) a forced cell merger in which the cell separation distance is larger than the cell core diameter; (c) a scenario in which the interacting cell cores overlap or the cell separation distance is smaller than the cell core diameter.
investigate whether the boundary layer scaling factor experiments have been conducted to further current study. They actually are of the simple type as defined in the view as the simple, forced, or overlapping type when time, traditional cell mergers between cells can be the overlapping type in the traditional sense. At the same note that the simple cell merger experiments between

characteristic length scales, it is useful to cause of the above-mentioned difference in the definitions of the characteristic length scales, it is useful to note that the simple cell merger experiments between interacting cell cores of this study may seem to be of the overlapping type in the traditional sense. At the same time, traditional cell mergers between cells can be viewed as the simple, forced, or overlapping type when they actually are of the simple type as defined in the current study.

In addition to the six baseline experiments, four sensitivity experiments have been conducted to further investigate whether the boundary layer scaling factor \( c_2 \) determined from the baseline experiments is valid for cell mergers with larger PBL depths (see Table 4). In all of the 10 experiments, the convective available potential energy (CAPE) of 2022 J kg\(^{-1}\) representative of the 9 August 1991 Convection and Precipitation/Electrification Experiment (CaPE) environment, is used. Both wind and wind shear are chosen to be absent for this study. These idealized ambient wind conditions may not be vastly different from the low-shear environments of the subtropical region of the Florida peninsula.

Section 2 gives an abbreviated background on the cell merger research, including the dissertation work of the first author of this paper (Stalker 1997). Stalker (1997) conducted coarse-resolution (250 m) simulations using a serial version of the current cloud model that could not computationally allow for the development of a robust relation between the PBL depth and the cell separation distance for cell mergers. For example, the characteristic cell core diameter was not even defined in that coarse-resolution study. However, Stalker (1997) has not only led to the current high-resolution modeling study, but also has led to the development of an objective method for convective cell identification useful for the cell merger research and for use in operational forecasting of severe thunderstorms (Stalker and Knupp 2002). Both Stalker (1997) and Stalker and Knupp (2002) utilized high-resolution multiple Doppler radar observations obtained during CaPE. These high-resolution radar observations have been used to understand both the microphysical and dynamical growth characteristics of various short-lived convective cells of the thunderstorm, to quantify some of the effects of cell mergers on updraft intensification and precipitation augmentation, etc. The interested reader is referred to Bringi et al. (1997), Stalker (1997), and Stalker and Knupp (2002) for a more detailed overview of the thunderstorm.

In section 3, a description of the cloud model, model setup for the idealized numerical experiments, a detailed discussion of the results of experiment 4 (a case of a simple cell merger), and a brief discussion on the numerically determined value of 0.5 for \( c_2 \) are included.

Table 1. Summary of cell separation distances found in previous studies. Here, NA stands for not available; SANS for same as no shear case.

<table>
<thead>
<tr>
<th>Study [dimension, resolution (m)]</th>
<th>Weak or no shear ( D \ (Z) )</th>
<th>Shear ( D \ (Z) )</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilkins et al. (1976) (2D, 100)</td>
<td>~400 (600)</td>
<td>NA</td>
<td>Tank observations.</td>
</tr>
<tr>
<td>Current study (3D, 100)</td>
<td>900 (1200)</td>
<td>NA</td>
<td>First 3D study with 100-m resolution.</td>
</tr>
<tr>
<td>Tao and Simpson (1984) (2D, 1000)</td>
<td>6000–10000 (variable)</td>
<td>SANS</td>
<td>Effects of large-scale lifting on cell merger investigated.</td>
</tr>
</tbody>
</table>

Table 2. Cloud hydrometeor representations in RAMS. Here, “P” stands for prognosed variable; “D” for diagnosed variable.

<table>
<thead>
<tr>
<th>Hydrometeor</th>
<th>Water phase</th>
<th>Mean diameter (mm)</th>
<th># density</th>
<th>Mixing ratio</th>
<th>Initial growth mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud water</td>
<td>Liquid</td>
<td>D</td>
<td>D</td>
<td>P</td>
<td>Vapor diffusion/autoconversion</td>
</tr>
<tr>
<td>Rainwater</td>
<td>Liquid</td>
<td>0.5</td>
<td>D</td>
<td>P</td>
<td>Collision coalescence</td>
</tr>
<tr>
<td>Pristine ice crystals</td>
<td>Solid</td>
<td>P</td>
<td>D</td>
<td>P</td>
<td>Vapor diffusion</td>
</tr>
<tr>
<td>Snow</td>
<td>Solid</td>
<td>1</td>
<td>D</td>
<td>P</td>
<td>Vapor diffusion</td>
</tr>
<tr>
<td>Aggregates</td>
<td>Solid</td>
<td>1</td>
<td>D</td>
<td>P</td>
<td>Collision coalescence</td>
</tr>
<tr>
<td>Graupel</td>
<td>Liquid + solid</td>
<td>1</td>
<td>D</td>
<td>P</td>
<td>Rimming</td>
</tr>
<tr>
<td>Hail</td>
<td>Liquid + solid</td>
<td>3</td>
<td>D</td>
<td>P</td>
<td>Rimming/melting</td>
</tr>
</tbody>
</table>
FIG. 2. Definitions of characteristic cloud length scales: (a) near-surface horizontal cross section showing the cloud diameter scaled from the PBL depth (McNider and Kopp 1990) and the cell core diameter scaled from the PBL depth (current study); (b) vertical cross section through the center of the cell showing cell and cell core diameters.

Section 4 summarizes the paper and includes some concluding remarks.

2. Background on cell merger

Multicell thunderstorms may contain several convective cells known as thunderstorm building blocks in their convective, mature, and dissipating stages of a cell lifetime (Byers and Braham 1949). While individual cells in the convective growth stage may differ in their vertical and horizontal dimensions and updraft intensity within a multicell thunderstorm, previous research has provided methods to estimate characteristic (bulk) updraft intensities and cell dimensions from the prestorm environmental conditions (e.g., Rogers and Yau 1991; McNider and Kopp 1990; Stalker and Knupp 2002). For example, the maximum updraft intensity within a convective cell may be related to the convective available potential energy based on the parcel theory (e.g., Rogers and Yau 1991). This maximum updraft intensity within a convective cell, also referred to as the thermodynamic speed limit (e.g., Bluestein et al. 1993), provides an estimation for the upper limit by relating upward motion \( U \) to \( \text{CAPE} \) [e.g., \( U = (2 \times \text{CAPE})^{1/2} \)]. In our recent paper, we have published a method that takes into account the diluting effects of the environment for the estimation of the actual maximum upward motion within a convective cell (Stalker and Knupp 2002). The characteristic horizontal dimension of a cell in the convective stage near cloud base has been shown to be controlled, at least partly, by the planetary boundary layer depth (e.g., McNider and Kopp 1990). On the other hand, the vertical dimension of a cell is capped by the upper tropospheric stable layer known to exist above the equilibrium level. Occasionally, deep convective cells are known to penetrate this upper-tropospheric stable layer. Since the updraft cell core reaches higher elevations only in the mature to dissipating stages, the vertical dimension should be determined later in the cell lifetime unlike the horizontal dimension.

Because of the coexistence of possible multiple cells in multicell thunderstorms, adjacent cells may interact both constructively and destructively in shaping the varied observed structures of multicell thunderstorms (e.g., Foote 1985). Additionally, previous research shows that merger can occur at many different horizontal scales other than the convective scales mentioned in the context of cell merger in this paper (e.g., Westcott 1977; Houze and Cheng 1977; Lopez 1978). The research findings presented in this paper can offer a plausible explanation on how upscale cloud growth may occur as the PBL grows in response to daytime heating. Particularly, a few noted constructive cell interactions investigated in previous studies are as follows: (i) the downdraft-induced outflow collision from the interacting cells forms a cloud bridge via new cloud growth (e.g., Simpson 1980; Simpson et al. 1980; Holle and Maier 1980; Cunning et al. 1982; Peterson 1984; Cunning and DeMaria 1986; Westcott and Kennedy 1989); (ii) the negative pressure gradient directed into the region between the interacting cells facilitates cell mergers (e.g., Orville et al. 1980; Turpeinen 1982; Tao and Simpson 1984, 1989); and (iii) the differential translational

### Table 3. Observed characteristics of prominent convective cells of the CaPE multicell thunderstorm.

<table>
<thead>
<tr>
<th>Number</th>
<th>Cell name</th>
<th>Time identified (UTC)</th>
<th>Peak updraft (m s(^{-1}))</th>
<th>Updraft area (km(^2))</th>
<th>Cloud top (km, AGL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>1755</td>
<td>18.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>1801</td>
<td>11.0</td>
<td>3.3</td>
<td>8.5</td>
</tr>
<tr>
<td>3</td>
<td>D</td>
<td>1803</td>
<td>18.0</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>4</td>
<td>E</td>
<td>1803</td>
<td>16.0</td>
<td>3.5</td>
<td>9.25</td>
</tr>
</tbody>
</table>
movement of the interacting cells may aid cell mergers (e.g., Cunning et al. 1982; Westcott and Kennedy 1989). Turpeinen (1982) showed that both cell interactions noted in (i) and (ii) above are important for cell mergers. Tao and Simpson (1989) showed that the formation of a cloud bridge can effectively produce a region that may experience favorable pressure gradients. The cell interaction noted in (iii) has been shown to occur in only a small fraction of the total number of cell mergers observed. The interaction noted in (iii) has been investigated using a three-dimensional model in a more recent study by Kogan and Shapiro (1996). In addition to the constructive cell interactions described above, a few noted destructive cell interactions have been previously investigated (e.g., Wilkins et al. 1976; Turpeinen 1982; Hill 1974; Kogan and Shapiro 1996). It has been qualitatively indicated in many of the above-mentioned studies and has been quantified via idealized simulations in other studies (e.g., Turpeinen 1982; Kogan and Shapiro 1996) that there exists a critical cell separation distance for successful cell mergers (see Table 1).

Several important questions still remain unanswered. 1) What is the minimum cell separation distance for a simple cell mergers? 2) What should be the maximum cell separation distance for which a forced cell merger is possible? 3) How must the cell or cell core diameter be defined for cell mergers? 4) What environmental variables control the cell merger process for developing forecasts of cell mergers? Both the current study and Stalker (1997) have answered a few of the above questions via three-dimensional numerical simulations.

3. Numerical experiments

a. Cloud model

1) GENERAL DESCRIPTION

A parallel version (version 4.3) of the Regional Atmospheric Modeling System (RAMS) has been used for the idealized cell merger modeling experiments. RAMS is intended for simulating mesoscale atmospheric motions with widely tested parameterized cloud microphysical processes (e.g., Meyers et al. 1992; Harrington et al. 1995; Walko et al. 1995). RAMS is a three-dimensional nonhydrostatic finite-difference model detailed in Pielke et al. (1992). For a general description of RAMS, the reader is referred to Cotton and Tripoli (1978), Tripoli and Cotton (1980, 1981), Cotton et al. (1982, 1986), Tripoli (1986), and Tremback (1990). The model solves a full set of compressible hydrodynamic equations and continuity equations for seven hydrometeor types in liquid, partially frozen (mixed), and completely frozen water phases. The drop or particle size distributions for these hydrometeors are based upon the generalized gamma distribution functions defined in Flatau et al. (1989) and Verlinde et al. (1990). The size distributions are defined in terms of a mean diameter and a
shape (dispersion) parameter for each hydrometeor type (e.g., Stalker and Bossert 1998). A value of 2 for the shape parameter is used for all categories in all cell merger experiments. The mean diameters used for rain, snow, graupel, and hail are 0.54, 1, 1, and 3 mm, respectively. Table 2 summarizes the parameterized cloud microphysical processes in the model.

2) CONVECTIVE CELL INITIATION

Convective cell initiation has been accomplished using a warm bubble in the horizontally homogeneous base state potential temperature obtained from the 9 August 1991 CaPE composite sounding. The magnitude of perturbation for the warm bubble is based on the boundary layer similarity technique of McNider and Kopp (1990). The perturbation in potential temperature within the warm bubble is defined as

$$\theta'(x, y, z) = A \sigma_0 \exp \left\{ - \left[ \frac{x - x_c}{0.5A_w} \right]^2 + \left[ \frac{y - y_c}{0.5A_w} \right]^2 \right\},$$

(1)
Here, $\sigma_p$ and $(\bar{w}\theta_e)$ are the standard deviation in potential temperature fluctuations and the surface heat flux, respectively. A value of 890 W m$^{-2}$ has been arbitrarily chosen for $(\bar{w}\theta_e)$ for this study. In the above formulation, the potential temperature perturbation exhibits a peak near the surface and goes to zero above the planetary boundary layer height within the center of the warm bubble in the vertical direction. In the horizontal direction, the potential temperature perturbation shows a peak in the center of the warm bubble and rapidly tapers off toward the edges (see Fig. 2b).

It is important to note that the initialization procedure used for the idealized experiments does not allow for the effects of sea-breeze collisions that are often known to produce thunderstorms in this area (Pielke 1974; Blanchard and Lopez 1985) nor does it allow for simulating all possible cell interactions and, thus, the overall observed multicell thunderstorm structure. However, warm bubble methods to initiate clouds have been successfully used in previous numerical studies on thunderstorm behavior (e.g., Weisman and Klemp 1984; Knupp et al. 1998). The above-mentioned limitations of the warm bubble method are not critical to achieve the goal of the current study to find the required cell separation distance for a successful cell merger.

b. Cell separation distance versus planetary boundary layer depth

1) ENVIRONMENTAL CONDITIONS AND COARSE-RESOLUTION NUMERICAL EXPERIMENTS

The Convection and Precipitation/Electrification Experiment was conducted in the summer months of 1991 to produce high-resolution observations of thunderstorm dynamical, microphysical, and electrical structures in the subtropical region of central Florida near Cape Canaveral [see Office of Project Support (1992) for details]. On 9 August 1991, the midtropospheric winds were weak (2.5–5 m s$^{-1}$), variable, and shifting from west-southwest to west-northwest, consistent with the movement of the surface high pressure center that moved to the south of the CaPE area during the day. This low-level flow provided the steering current for the western sea-breeze front to move inland. Strong upper-level easterly winds (17.5–20 m s$^{-1}$) were present near the 200-mb level. The average relative humidity was ~65% within a deep layer that extended from the surface up to 6 km above ground level (AGL). Drier conditions existed above this deep moist layer.

The high-resolution multiple (three) Doppler radar observations obtained during CaPE have been used in all phases of the research. For example, the radar data have been used for the identification of several prominent convective cells within the thunderstorm. The radar data guided the convective cell initiation procedure used for the idealized numerical experiments and for model validation when applicable. Particularly, these data revealed the multicellular structure of the thunderstorm with two distinct groups of convective cells (see Bringi et al. 1997; Stalker 1997; Stalker and Knupp 2002). Each group of convective cells contained at least one stronger convective cell and experienced a cell merger (Stalker 1997). Some convective cell characteristics of four prominent cells identified, within the two groups, using the cell identification method of Stalker and Knupp (2002), are given in Table 3. Our cell-naming convention is chronological and differs from Bringi et al. (1997).

Using the 9 August 1991 composite sounding (Fig. 3) to initialize a serial version of RAMS (version 3b), Stalker (1997) showed, without ambient wind or wind shear, that cell mergers between interacting convective cells are possible for a cell separation distance of ~2 km. Stalker (1997) used a coarse-resolution (250 m), limited-area domain (121 × 121 × 43) for these idealized numerical experiments. Additionally, Stalker (1997) conducted other idealized experiments with observed wind and wind shear and determined a cell separation distance of ~2.8 km for cell mergers when the interacting cells are oriented parallel to the mean shear vector. It was also shown in that study that cell mergers were not possible when the cells were oriented perpendicular to the mean shear vector. Stalker (1997) attributed this increase in cell separation distance with wind and wind shear to favorable modifications of entrainment. In other words, entrainment of environmental air into the interacting cells may be significantly reduced if the cell orientation is parallel to the mean shear vector. Other previous studies indicated similar influences of

<table>
<thead>
<tr>
<th>Expt</th>
<th>$D_0$ (m)</th>
<th>Peak updraft (m s$^{-1}$), level (m), time (min)</th>
<th>Peak rain mixing ratio (g kg$^{-1}$), level (m), time (min)</th>
<th>Peak cloud water mixing ratio (g kg$^{-1}$), level (m), time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1200</td>
<td>22.0, 4500, 26</td>
<td>4.25, 4500, 26</td>
<td>3.1, 2500, 21</td>
</tr>
<tr>
<td>2</td>
<td>1100</td>
<td>21.5, 4500, 26</td>
<td>4.25, 4500, 26</td>
<td>3.1, 2500, 21</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>21.5, 4500, 26</td>
<td>3.75, 4500, 26</td>
<td>3.1, 3000, 22</td>
</tr>
<tr>
<td>4</td>
<td>900</td>
<td>21.5, 4000, 29*</td>
<td>2.50, 4000, 29</td>
<td>3.1, 3000, 23</td>
</tr>
<tr>
<td>5</td>
<td>700</td>
<td>20.0, 4250, 24</td>
<td>4.50, 5000, 28</td>
<td>2.9, 2750, 22</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>23.5, 4000, 24</td>
<td>7.50, 5000, 26</td>
<td>3.1, 2750, 20</td>
</tr>
<tr>
<td>7</td>
<td>1200</td>
<td>23.0, 4000, 24*</td>
<td>7.50, 3250, 32</td>
<td>3.1, 2750, 20</td>
</tr>
<tr>
<td>8</td>
<td>1500</td>
<td>26.0, 4500, 25*</td>
<td>12.50, 3900, 33</td>
<td>3.1, 2750, 20</td>
</tr>
<tr>
<td>9</td>
<td>2000</td>
<td>28.0, 5000, 27*</td>
<td>13.00, 3900, 33</td>
<td>3.0, 3000, 22</td>
</tr>
<tr>
<td>10</td>
<td>2500</td>
<td>28.0, 5000, 29*</td>
<td>15.00, 3500, 35</td>
<td>3.0, 2750, 24</td>
</tr>
</tbody>
</table>

* Before cell merger.
** After cell merger.
FIG. 5. A convective cell merger is shown at higher elevations between adjacent updraft cores in experiment 4 using vertical cross sections through interacting cell centers: vertical motion at (a) 24, (b) 27, (c) 30, and (d) 32 min; contours of $-4, -2, 2, 6, 10, 14,$ and $18 \text{ m s}^{-1}$ are shown.

entrainment on cell mergers (e.g., Byers and Braham 1949; Lopez 1978; Wiggert et al. 1981).

The findings of Stalker (1997) on the cell separation distance for cell merger are in general agreement with many previous modeling studies, although Stalker (1997) produced the simulations using limited computational resources available at the time. Because of the computationally allowable limited horizontal extent of the domain ($\sim 30 \text{ km}$), especially with coarse horizontal resolution, unrealistically stronger (larger amplitude) and deeper (larger wavelength) perturbations were used to initiate convection in numerical models using warm bubbles (e.g., Weisman and Klemp 1984). Such stronger perturbations were known to be required to compensate, for example, for the significant lateral boundary influences on the model solutions of limited-area simulations. For Stalker (1997), this requirement of deeper perturbations meant an unrealistically deeper boundary layer depth for deep convective motions to develop within the numerically simulated convective cells against the unrealistically larger suppressing effects of the lateral boundaries. The recollection of the first author of this paper indicates that deep convective motions were suppressed with the observed PBL depth of only 1200 m, irrespective of the strength of perturbation or how warm the bubble was made relative to the envi-
Fig. 6. A convective cell merger is shown at lower elevations between adjacent rain cores in experiment 4 using vertical cross sections through interacting cell centers: rain mixing ratio at (a) 24, (b) 27, (c) 30, and (d) 32 min; contours of 0.5, 1, 1.5, 2, 2.5, 3, and 3.5 g kg\(^{-1}\) are shown. In (c) and (d), an additional contour of 0.1 g kg\(^{-1}\) is also shown to clearly indicate cell merger between the original cells.

2) HIGH-RESOLUTION NUMERICAL EXPERIMENTS

A large single grid (301 \(\times\) 301 \(\times\) 56) with a horizontal grid spacing of 100 m has been used in all of the idealized high-resolution numerical experiments. The vertical grid spacing has been varied from 100 m in the lowest levels to 400 m in the upper portions of the domain. The vertically varying grid setup resolves a model depth of 18 977 m. Such comparable horizontal and vertical grid spacings (or aspect ratios of \(\sim\)1), especially for the lowest model levels, have been made possible with the recent developments in computational techniques and resources. Only much smaller aspect ratios were computationally allowed in the past three-dimensional modeling studies (e.g., Stalker 1997) on deep convection. Smaller aspect ratios are known to be less desirable for the subgrid turbulence parameteriza-
A peak upward motion of 23 m s\(^{-1}\) was simulated in this experiment; a peak rainwater mixing ratio of 7 g kg\(^{-1}\) was simulated in this experiment. Upward motion contours of 5, 8, 15, 20, and 23 m s\(^{-1}\) are shown. Rain mixing ratio contours of 0.5, 1.5, 2.5, 3.5, 4, 6, and 7 g kg\(^{-1}\) are shown.

A long time step of 0.5 s for the slow mode horizontal advective terms and a small time step of 0.1 s for the fast mode acoustic terms have been used in all 10 experiments listed in Table 4 (Walko and Tremback 1998). The first six experiments have the same PBL depth of 1200 m. In these six experiments, the cell separation distance between the interacting cell cores has been varied from 1200 m (experiment 1) to 500 m (experiment 6). A cell merger has been simulated only in experiment 4 with a cell separation distance of 900 m. This cell separation distance of 900 m scales as 0.75 times the PBL depth (i.e., 900 m = 0.75 \times 1200 m). The coarse-resolution simulations of Stalker (1997) without ambient wind and wind shear show a comparable boundary layer scaling for the cell separation distance for simple cell mergers; that is, \(\approx 2000 \text{ m} = 0.67\) times the PBL depth of 3000 m.

Cell mergers have not been simulated in the remaining five baseline experiments for different reasons. The cell separation distance in experiments 1–3 points to the scenarios of forced cell mergers (see Fig. 1). Additional forcing mechanisms such as those induced by ambient wind shear may be necessary for cell mergers as suggested from the coarse-resolution simulations of Stalker (1997). From the coarse-resolution simulations of Stalker (1997) with ambient wind and wind shear, the cell separation distance was scaled as 0.93 times the PBL depth for forced cell mergers. Future high-resolution simulations will be required to quantify the exact boundary layer scaling for the cell separation distance for forced cell mergers. The cell separation distance in experiments 5 and 6, on the other hand, points to the overlapping scenarios in which the initial cell cores overlap and, thus, are considered physically invalid scenarios for cell mergers in this study (Fig. 1).

Deep convection starts to develop in all of the 10 experiments 15 min after the cell initiation. Since a cell merger has been simulated only in experiment 4, the following discussion is based on the results of this experiment unless explicitly stated otherwise. The time–height sections of peak upward motion (Fig. 4a) and peak rainwater mixing ratio (Fig. 4b) clearly show the effects of cell merger. For example, upon cell merger at 27 min, evidence of reintensiﬁcation of upward motion is present. This is not the case in experiment 1 in which only a single updraft pulse has been simulated (Fig. 4c). Although the peak upward motion is not as strong as in experiment 1, the merged cells show increased longevity. Similarly, other effects of cell merger, such as a longer-lasting rain core, are also evident in the peak rainwater mixing ratio (Fig. 4b). However, the peak rainwater mixing ratio is comparable to experiment 1 (see Figs. 4b,d). The time–height sections of experiments 2 and 3 are not included in this discussion since these simulations produced characteristics of upward motion and rainwater similar to experiment 1 (see Table 5 for details). The results of experiments 5 and 6 are not discussed further in this paper, although some simulated differences in the strength of the detrimental effects of adjacent cells may be noteworthy (see Table 5 for details).

Vertical cross sections of upward motion and rainwater mixing ratio through the cell cores are shown at 24, 27, 30, and 32 min (Fig. 5). These cross sections...
show how upward motion develops in the individual cell cores initially as shown in Figs. 5a,b before producing a contiguous merged updraft region or a cell merger at 30 min (see Fig. 5c) at higher elevations (>3500 m AGL). Reintensification of upward motion upon cell merger is also shown in the vertical cross section of Fig. 5d at 32 min. At the lower levels (<3500 m AGL) during this advanced stage, particularly within the original cells, downward motions are simulated. Regions of downward motion are known to exist within active convective cells due to, for example, rainwater loading (e.g., Srivastava 1967; Knupp 1985). These downdrafts are also known to induce surface wind outflows from which a region of convergence between the original cells is produced. Within this newly formed region of convergence, secondary cloud growth appears to force a cloud bridge between the interacting cells near cloud base. An in-depth analysis of the various cell merger processes that may be responsible for the cell merger is not given here since such an analysis is outside the scope of the research reported in this paper. However, such an analysis may show that many previously noted cell interactions may be producing important synergistic effects in the cell merger.

The corresponding vertical cross sections of rain mixing ratio show the cell merger in terms of rainwater at 30 and 32 min more distinctly as shown in Figs. 6c and 6d, respectively. The smaller rainwater mixing ratio
Fig. 9. A convective cell merger is shown at lower elevations between adjacent rain cores in experiment 7 using vertical cross sections through interacting cell centers: rain mixing ratio at (a) 24, (b) 27, (c) 30, and (d) 32 min; contours of 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 5, and 7 g kg$^{-1}$ are shown.

To further investigate the boundary layer scaling for the cell separation distance determined in experiment 4, four sensitivity experiments (7–10), with PBL depths of 1600 m (experiment 7), 2000 m (experiment 8), 2670 m (experiment 9), and 3333 m (experiment 10), have also been conducted. The time–height sections of peak upward motion (Fig. 7) of experiment 7 show similar two-pulse updraft structure simulated in experiment 4. In the upper portions within the cloud layer (above 4000 m), these updraft pulses are not as contiguous as in experiment 4. The region of weaker upward motion ($<5$ m s$^{-1}$) that exists between these two pulses indicates appreciable water loading with a rainwater mixing ratio of 7 g kg$^{-1}$ (Fig. 7b). Vertical cross sections of upward motion and rainwater mixing ratio at 24, 27, 30, and 32 min, respectively, are shown in Figs. 8 and 9 for ex-
experiment 7. Similar to experiment 4, a cell merger is evident aloft from the merged updrafts at 27 min (Fig. 8b). The merged updrafts do not last as long as in experiment 4 due to excessive water loading. In order to show cell mergers using upward motion, cell mergers must not only be depicted at higher elevations for the reasons mentioned before, but the longevity of such a merged updraft may be inversely proportional to the amount of rainwater. In other words, the larger rainwater mixing ratios produced in the sensitivity experiments allow for only brief depictions of cell mergers in terms of upward motion. A cell merger is clearly shown in terms of rainwater from the corresponding vertical cross sections of rain mixing ratio at 27 min (Fig. 9b) and at 30 min (Fig. 9c) for experiment 7. Experiment 8 produces similar cell merger characteristics, although the merged updraft exhibits even a shorter duration compared to experiment 7. For example, experiment 8 exhibits a similar two-pulse updraft structure as in experiment 7, except the updraft cores are comparatively deeper (Fig. 10a). A larger value of 12 g kg$^{-1}$ for the peak rainwater mixing ratio is simulated in experiment 8 (Fig. 10b). From the corresponding vertical cross sections of upward motion (Fig. 11) and rainwater mixing ratio (Fig. 12) for experiment 8, a cell merger is briefly simulated between the updraft cores at 27 min (Fig. 11b) and at 30 min (Fig. 11c) and between the rainwater cores at 27 min (Fig. 12b) and at 30 min (Fig. 12c). The unrealistically larger rain mixing ratios simulated in experiment 9 (13 g kg$^{-1}$) and in experiment 10 (15 g kg$^{-1}$) do not allow for the depiction of cell mergers in terms of updrafts as such cell mergers last very briefly. However, the boundary layer scaled cell separation distance for these sensitivity experiments shows the potential for cell mergers. For example, the time–height section of peak upward motion in experiment 9 shows the two-pulse updraft structure as in the previous experiments (Fig. 13a). Figure 13a also shows that the area of weaker upward motion between the two updraft pulses is deeper for this experiment, indicative of the presence of detrimental effects of excessive water loading within a deeper cloud layer. The results of experiments 9 and 10 suggest that other aspects of the microphysical cell evolutions that are strongly dependent on CAPE and the available moisture content of the environment may have to be taken into account in order to develop a more appropriate boundary layer scaling within deeper planetary boundary layers for the cell separation distance. For example, the numerically determined value of 0.5 for $c_2$ may show sensitivity to both CAPE and moisture content of the environment. The monotonic increases, shown for the sensitivity experiments, in the peak upward motion and rainwater mixing ratio as a function of the PBL depth may offer quantitative ways to diagnose both updraft vigor and precipitation from pre-storm environmental conditions (Table 5).

4. Summary and discussion

Important environmental factors that may control the convective cell merger process such as the planetary boundary layer (PBL) depth, the convective available potential energy (CAPE), vertical shear of the horizontal wind, etc., have been discussed. Also, the importance of developing an understanding into the cell merger process has been discussed in the context of possible aug-
Fig. 11. A convective cell merger is shown at higher elevations between adjacent updraft cores in experiment 8 using vertical cross sections through interacting cell centers: vertical motion at (a) 24, (b) 27, (c) 30, and (d) 32 min; contours of $-4, -2, 2, 6, 10, 14, 18, 20, 22, 24,$ and $26 \text{ m s}^{-1}$ are shown.

The qualitative nature of the existing cell and cell merger definitions have been noted. The difficulties in simultaneously using both upward motion and rainwater to depict cell mergers have been clarified. For example, cell mergers must be depicted in terms of upward motion at higher elevations where relatively stronger upward motions exist during advanced stages of cell mergers. On the other hand, cell mergers must be indicated in terms of rainwater at lower elevations where rainwater tends to accumulate at the advanced stages.

Various shortcomings in previous modeling studies, including Stalker (1997), have been noted, especially with regard to the required horizontal model resolution and the associated need for increased computational resources for successful simulations of cell mergers. In spite of many previous modeling and observational studies, a uniquely determined cell separation distance for cell mergers does not exist to date, not to mention the lack of a relationship between specific environmental variables and cell mergers. Also, the approaches in many of the previous studies were about determining certain cell interactions such as the pressure gradient force, etc., responsible for cell mergers and not about developing a method to diagnose cell mergers. Computational resources prior to the advent of parallel computing may have been the most limiting consideration in the previous modeling approaches. However, the need
to further understand the cell merger process remains for the following reasons:

- to increase cell merger predictability given the ambient conditions;
- to better represent effects of cell merger in, for example, cumulus parameterization schemes employed in coarse-resolution regional climate models;
- to identify critical processes that lead to precipitation augmentation and to potentially improve cloud seeding efforts; and finally,
- to improve forecast lead times for severe weather phenomena (e.g., flash flooding, lightning, and destructive wind gusts).

The authors acknowledge that there may be several other critical reasons not mentioned here for the understanding of the cell merger behavior.

The current study has addressed some of the above important issues by using high-resolution numerical experiments and very high-resolution triple Doppler radar observations. Doppler radar observations have been used in many aspects of the idealized numerical experiments, that is, in the depiction of storm microphysical and dynamical structures, in the determination of a characteristic cell separation distance for cell mergers within the 9 August CaPE multicell thunderstorm, and in the model initialization procedure. A total of 10 experi-
ments with a horizontal grid spacing of 100 m have been conducted in this study. These idealized experiments show that the cell separation distance for a simple cell merger is 0.75 × Z from the baseline experiment 4. Also, four sensitivity experiments show that the boundary layer scaling for the cell separation distance determined in experiment 4 is valid for diagnosing simple cell mergers as long as the PBL depth Z is not unrealistically large (>2700 m). When the PBL depth is extremely large as in experiments 9 and 10, the excessive water loading indicated by large rainwater mixing ratios can make cell merger depiction using upward motion difficult since the merged updraft regions may only last for brief periods. On the other hand, cell merger depictions in terms of rainwater are relatively straightforward even for larger PBL depths.

This numerical investigation shows that the PBL depth along with the characteristic cell separation distance, determined from a boundary layer scaling factor (0.75), can be used to diagnose the potential for cell mergers between any interacting convective cells and to possibly quantify the effects of cell merger on updraft vigor and precipitation augmentation. The monotonic increases in updraft and precipitation as a function of the PBL depth can be used to build effective subgrid parameterizations of the cell merger process for coarse atmospheric models. However, future numerical investigations must include other factors such as environmental wind and wind shear to further examine the boundary layer scaling for cell mergers of the forced type defined in this study. Additionally, future investigations must address the sensitivities of low- and high-CAPE environments on the boundary layer scaling for the cell separation distance determined in this study. It is also important to note that this paper has not specifically discussed all the forcing mechanisms of convergence within the PBL. For example, boundary layer convergence resulting from the interaction of pre-existing convective boundary layer rolls and their orientation relative to the sea-breeze fronts common in this environment (e.g., Wakimoto and Atkins 1994; Atkins and Wakimoto 1995) may provide a forcing mechanism for the formation of convective cells with the favorable characteristic cell separation distance for cell mergers. In addition to the effects of ambient wind shear, further numerical investigation may be necessary to determine the sensitivity of the above-mentioned forcing mechanisms on the planetary boundary layer scaling determined in this study.

Additionally, efforts should be made to quantify the importance of large-scale low-level convergence associated with surface low pressure regions and other processes that may produce large-scale convergence. Key dynamical processes such as the pressure gradient force, microphysical processes such as water loading, exchange of hydrometeors between the interacting cells, and both resolved and subgrid entrainment need to be numerically investigated further to greatly improve our ability to incorporate the effects of cell mergers into coarse-resolution atmospheric models.

An important application of the boundary layer scaling determined in this study may be to help understand how upscale cloud growth occurs, for example, via mergers between thermals and smaller convective cells, while the planetary boundary layer depth increases during the day in response to daytime heating. This type of research into the cell merger process can immensely improve the algorithms implemented in the current radar
data retrieval techniques of, for example, the Next Generation Weather Radar (NEXRAD) network of the United States.

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APPENDIX

List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Constant to define a thermal perturbation (nondimensional)</td>
</tr>
<tr>
<td>c1</td>
<td>Planetary boundary layer scaling factor (nondimensional)</td>
</tr>
<tr>
<td>c2</td>
<td>Constant to relate cell and cell core diameters (nondimensional)</td>
</tr>
<tr>
<td>CAPE</td>
<td>Convective available potential energy (J kg⁻¹)</td>
</tr>
<tr>
<td>Dc</td>
<td>Cell core diameter (m)</td>
</tr>
<tr>
<td>Ds</td>
<td>Cell separation distance (m)</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational constant (m s⁻²)</td>
</tr>
<tr>
<td>λₚ</td>
<td>Perturbation length scale or cell diameter (m)</td>
</tr>
<tr>
<td>λc</td>
<td>Length scale of cell core diameter (m)</td>
</tr>
<tr>
<td>σθ</td>
<td>Standard deviation in potential temperature fluctuations (K)</td>
</tr>
<tr>
<td>θ</td>
<td>Potential temperature (K)</td>
</tr>
<tr>
<td>θ’</td>
<td>Perturbation in potential temperature (K)</td>
</tr>
<tr>
<td>U</td>
<td>Upward motion (m s⁻¹)</td>
</tr>
<tr>
<td>wθₕ</td>
<td>Heat flux at surface [K (m s⁻¹)]</td>
</tr>
<tr>
<td>x</td>
<td>East–west coordinate (m)</td>
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<tr>
<td>xₜ</td>
<td>Center x coordinate of perturbation (m)</td>
</tr>
<tr>
<td>y</td>
<td>North–south coordinate (m)</td>
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<tr>
<td>yₜ</td>
<td>Center y coordinate of perturbation (m)</td>
</tr>
<tr>
<td>z</td>
<td>Vertical coordinate (m)</td>
</tr>
<tr>
<td>Z</td>
<td>Planetary boundary layer depth (m)</td>
</tr>
</tbody>
</table>

REFERENCES


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—–, and W. R. Cotton, 1980: A numerical investigation of several factors leading to the observed variable intensity of deep convection over south Florida. J. Appl. Meteor., 19, 1037–1067.


