A Method to Identify Convective Cells within Multicell Thunderstorms from Multiple Doppler Radar Data

JAMES R. STALKER

Atmospheric and Climate Sciences Group, Los Alamos National Laboratory, Los Alamos, New Mexico

KEVIN R. KNUPP

Department of Atmospheric Science, Global Hydrology and Climate Center, University of Alabama in Huntsville, Huntsville, Alabama

11 July 2000 and 22 June 2001

ABSTRACT

Convective cell identification methods, besides their operational utility, are useful to identify cells, to understand cell interactions within multicell thunderstorms, and to distinguish between convective and stratiform regions within mesoscale convective systems. The method developed in this note was utilized for research on cell interactions within the 9 August 1991 Convection and Precipitation/Electrification (CaPE) multicell thunderstorm. A critical component of such research is an objective method to accurately depict all significant convective cells within an evolving multicell thunderstorm. While conventional methods based upon radar reflectivity can be successfully used in identifying cells, especially when the cells are in their growth stage, the methods are not as useful during the later stages of cell growth. This is because updraft and precipitation cores are not collocated at these advanced stages, and thus the reflectivity (precipitation) core may not be a good indicator of convectively active regions. The method presented in this note uses four objective criteria to define and identify convective cells within multicell thunderstorms. These criteria are chosen from a prestorm proximity sounding using the air parcel theory. The four objective criteria and their threshold values for the CaPE storm included in parentheses are 1) a *threshold updraft* W_d ($\sim$8 m s^{-1}), 2) a *threshold cloud-layer depth* D_d ($\sim$4.9 km), 3) a *threshold updraft area* A_d ($\sim$1 km^2), and 4) *cell origin within the planetary boundary layer* indicated by the W_{pbl} ($\sim$3 m s^{-1}) contour. Since the method is based upon upward motion and not reflectivity factor, *multiple* Doppler radar data are required to utilize this method.

1. Introduction

Precipitating convection exhibits configurations ranging from large, long-lived unicellular structures to short-lived multicellular forms consisting of ordinary cells (Foote 1985). Byers and Braham (1949) showed that a convective (ordinary) cell typically goes through three stages during an approximate 45-min lifetime: (a) the cumulus stage, (b) the mature stage, and (c) the dissipating stage. During its cycle, a convective cell develops an updraft core, a precipitation core, and lateral entrainment and cloud-top detrainment circulations (e.g., Yuter and Houze 1995). Upon entering the mature stage, downdrafts may be initiated by water loading, evaporation, and/or melting (e.g., Srivastava 1985, 1987; Knupp 1988). Thus, updraft and precipitation cores are not collocated at this mature stage and beyond (e.g., Bringi et al. 1997). Due to the abovementioned vertical displacement between updraft and precipitation cores at the advanced stages of cell development, precipitation-based cell identification methods that only use radar reflectivity factor Z are less useful in identifying convective cells.

Partial motivation for this research was provided by the interest to further understand the relation between updraft and precipitation (i.e., Z) cells. These two variables are known to be related to the parcel residence time that can vary from $\sim$10 min in deep convective clouds with stronger upward motion of $\sim$30 m s^{-1} to $\sim$20 min in weaker convective clouds of the isolated type (e.g., Cotton and Anthes 1989). However, there remains an unanswered question: What cloud updraft properties (e.g., updraft magnitude, updraft area, convective growth period, etc.) are required to produce precipitating convection? In addition to providing answers to the above question, it is critical to identify convective

Corresponding author address: Dr. James R. Stalker, EES-8, Mail Stop D401, Los Alamos National Laboratory, Los Alamos, NM 87545.
E-mail: stalker@lanl.gov

TABLE 1. Four parameters used in 9 Aug CaPE storm.

Parameter	Numerical value
Diluted updraft (W_d)	7 m s^{-1}
Cloud-layer depth (D_d)	4.6 km
Updraft area (A_d)	1 km^2
Updraft within PBL	3 m s^{-1}

regions within individual cells of multicell thunderstorms to understand cell interactions and possible merging of cells. Cell merging within multicell thunderstorms was investigated by several researchers because of a possible increase in total precipitation from the merged cell compared to precipitation from the individual cells without merging (e.g., Simpson 1980; Simpson et al. 1980).

The aforementioned need for an objective method to identify convective cells has motivated us to develop a new cell identification method presented in this note, to define and identify convective cells during the entire lifetime. This method uses a high-resolution time series of upward motion derived from *multiple* Doppler radar data. Threshold values for the four criteria have been chosen and generalized based upon the 9 August 1991 Convective and Precipitation/Electrification (CaPE) multicell thunderstorm (hereafter the storm).

2. Generalized relations for the criteria

Generalized relations for the criteria for defining and identifying a convective cell are developed based upon air parcel theory so their applicability can be extended to cell identification within multicell thunderstorms of different environments. The convective available potential energy (CAPE) obtained from a prestorm sounding is used in the above relations. These generalized relations are based upon four parameters (see Table 1) used in successfully identifying many convective cells within the storm that evolved in the low-shear subtropical environment of Florida (Stalker 1997). The four objective criteria are schematically shown in Fig. 1.

According to the parcel theory, a parcel of air rises at the moist-adiabatic lapse rate in an unstable environment (e.g., Rogers and Yau 1991). Some notable limiting assumptions of this theory are (i) the parcel does not mix with the environment, (ii) aerodynamic drag on the parcel is neglected, and (iii) loading of condensed water is neglected. However, for a given magnitude of boundary layer convergence and upon assuming no preexisting convection and the associated possible secondary convection at low levels that can lessen the representativeness of the sounding, the parcel theory can provide an estimate of the maximum achievable updraft within an environment. This maximum upward motion occurs at a height (z_{max}) on the sounding found between the level of free convection (z_{lfc}) and the cloud-top height (z_{ct}). We refer to this maximum upward motion as the adiabatic upward motion W_a. Other variables de-

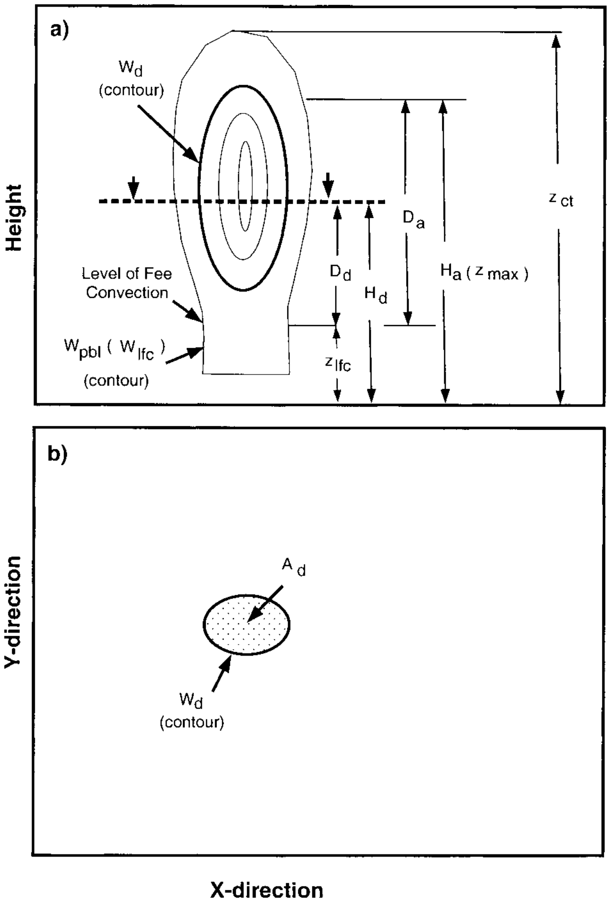

FIG. 1. (a) Vertical cross section through a convective cell core. The $W_{pbl}(W_{lfc})$ contour shows that the cell origin is within the PBL. Also shown is the threshold cloud-layer height (H_d) where a minimum updraft strength of W_d must develop. [The dark dashed line indicates the height where the horizontal cross section is shown for (b).] (b) The shaded region bounded by the W_d contour shows the threshold updraft area or upward mass flux at H_d for precipitating convection.

fined using the adiabatic assumption include the adiabatic cloud-layer height (H_a) and the adiabatic cloud-layer depth (D_a). The counterparts of the above variables within an actual environment are defined as W_d, H_d, and D_d, respectively.

Upon integrating a simplified vertical equation of momentum without water loading and pressure perturbation effects, the adiabatic maximum upward motion (W_a) is expressed as

$$\frac{W_a^2}{2} = \frac{W_{lfc}^2}{2} + g \int_{z_{lfc}}^{z_{max}} \left(\frac{T_a}{T_e} - 1\right) dz, \qquad (2.1)$$

where T_a is the adiabatic parcel temperature and T_e is the environmental temperature, dz is the elemental depth, and W_{lfc} is the updraft at the level of free convection. The second term on the right-hand side of (2.1) can be expressed as a product of CAPE and a fraction (c) to subtract the amount of CAPE remaining between z_{max} and z_{ct}. The value to be chosen for c must reflect the depth where the maximum upward motion may occur within the cloud layer. A value of 0.75 has been chosen for c in this study to indicate that the adiabatic maximum upward motion occurred above a deeper cloud layer ($3/4 \times D_a$). This fraction (c) can be precisely estimated from a proximity sounding by determining the height where the adiabatic parcel temperature achieves a maximum relative to the environment and the equilibrium level.

Equation (2.1), then, reduces to the following:

$$W_a = \sqrt{W_{\mathrm{lfc}}^2 + 2 \times c \times \mathrm{CAPE}}. \tag{2.2}$$

a. *Criteria*

1) Threshold diluted updraft (W_d)

In an actual environment, dilution by entrainment of subsaturated air into the cloud volume occurs. Precipitating convection occurs if this dilution is not excessive while nonprecipitating convection results in the presence of excessive dilution (e.g., Byers and Braham 1949). To account for the dilution in actual environments, the adiabatic variables obtained from proximity soundings are adjusted using a dilution coefficient d.

We define the threshold diluted updraft (W_d) to be the first criterion for identifying a precipitating convective cell. This criterion allows for the required amount of upward motion while a cell is growing against the diluting effects of its environment:

$$W_d = W_a \times d, \tag{2.3}$$

where W_d can also be written as the following using (2.1) and (2.3):

$$W_d = d \times \sqrt{W_{\mathrm{lfc}}^2 + 2 \times c \times \mathrm{CAPE}}. \tag{2.4}$$

Depending on the environment, d can vary between 0 and 1. Larger values of d indicate stronger dilution and less likelihood of precipitating convection. A detailed discussion on the factors that may influence d is beyond the scope of this note. We suggest that the following environmental factors may be important: (i) wind profile (e.g., vertical shear of the horizontal wind), (ii) temperature and water vapor profiles (e.g., CAPE), (iii) cell dimension, (iv) the airmass type (e.g., continental vs maritime), and (v) boundary layer convergence.

2) Threshold cloud-layer depth (D_d)

Once the threshold updraft is determined for a precipitating convective cell, sufficient parcel residence time required for microphysical processes to produce precipitation should be determined.

This parcel residence time ($t_{p(d)}$) is related to the second objective criterion of the threshold cloud-layer depth (D_d or the threshold cloud-layer height, $H_d = D_d + z_{\mathrm{lfc}}$) as below:

$$W_d = \frac{D_d}{t_{p(d)}}. \tag{2.5}$$

Similarly, W_a can be written as

$$W_a = \frac{D_a}{t_{p(a)}}, \tag{2.6}$$

where D_d is then determined from (2.5) and (2.6) as shown below:

$$D_d = t_{p(d)} \times d \times \sqrt{W_{\mathrm{lfc}}^2 + 2 \times c \times \mathrm{CAPE}}. \tag{2.7}$$

Since the criteria developed here are more concerned with the maxima/minima than the actual quantities for defining and identifying precipitating convective cells, W_d is used in (2.5) instead of upward motion as a function of height within the cloud layer to determine the threshold depth. In other words, (2.5) assumes that an upward motion of W_d exists in the entire cloud layer. Because of the conservative nature of this assumption, the threshold cloud-layer depth determined from (2.5) indicates an upper limit. If desired, further adjustment in both cloud-layer depth and parcel residence time can be made without changing the criteria. The absolute minimum parcel residence time $t_{p(\min)}$ and the absolute maximum parcel residence time $t_{p(\max)}$ for precipitating convection are defined in such a way that the threshold cloud-layer depth D_d and the adiabatic cloud-layer depth D_a are equal as d approaches 1. In other words, D_d increases with increased dilution of the environment only to approach D_a when the dilution is 100% (or $d = 1$).

Based on the above assumptions and using (2.3), (2.5), and (2.6) we have,

$$D_d = D_a\left[\frac{t_{p(\min)}}{t_{p(\max)}}\right]. \tag{2.8}$$

Using D_d estimated from (2.8), a first-order approximation of the dilution coefficient d for a particular environment can be made from (2.3) as follows:

$$d = \frac{D_d}{t_{p(\min)} \times \sqrt{W_{\mathrm{lfc}}^2 + 2 \times c \times \mathrm{CAPE}}}. \tag{2.9}$$

3) Threshold updraft area (A_d or upward mass flux $\rho A_d W_d$)

The first two criteria assure the amount of buoyancy required against environmental dilution and minimum cell lifetime for precipitation development. The horizontal dimension of the cell also influences entrainment and, thus, is the third important criterion in defining a precipitating convective cell. Previous studies defined relations between upward motion (or upward mass flux) and entrainment (e.g., Houze 1993). Previous studies also showed that entrainment rate is inversely proportional to the horizontal dimension of the cell (e.g., Simpson 1971). In other words, larger cells may experience lesser entrainment under the same environmental conditions than smaller cells and hence are capable of producing precipitation. In addition to the dynamic aspect of this criterion, there is another equally important reason why this criterion should be satisfied during the convective stage of the cell. This latter constraint of the criterion eliminates false cell identification resulting from coarse radar data interpolation to a fine Cartesian grid. If A_d is less than $4\Delta x^2$ (where Δx is the horizontal grid spacing of the fine Cartesian grid that the raw radar data are interpolated to) at H_d, then cells may be spuriously identified.

4) CONVECTIVE CELL ORIGIN

This fourth criterion is desirable to ensure that a convective cell is identified during the convective growth stage. We require that a minimum updraft (W_{pbl}) be present in a cloud-free layer beneath a cell, extending into the planetary boundary layer (PBL) during the growth stage. Similar assumptions were made to establish the growth stage of convective cells in previous studies (e.g., Arakawa and Schubert 1974). We also assume that W_{pbl} and W_{lfc} are identical in this note. Errors in accurately determining upward motion within the PBL are significant, for example, in the presence of echo-free regions, due to the method of integration used, etc. This possible inaccuracy in determining W_{pbl} does not present a severe limitation for the method as W_a is significantly larger compared to W_{pbl}. Caution, however, should be used in choosing W_{pbl} as it may require some trial-and-error procedure.

This criterion also helps differentiate between new cells that may originate from the lowest levels (near cloud base) and cells that may originate aloft due to adjacent updraft outflow collisions. We designate mature and dissipating cells with one or more primes over their designated letters depending on whether a cell is in its mature or dissipating stage, respectively. This differentiation between growing and dissipating cells is not only convenient but also appropriate as cells sequentially go through the three stages during the lifetime. Convective cells originating at mid- to upper levels due to updraft outflow collisions are not explicitly identified by these criteria.

b. *Threshold values for the storm*

In this section, the threshold values are determined for the storm using the generalized relations. The following information can be obtained from the prestorm sounding shown in Fig. 2. The height of the level of free convection z_{lfc} is ~1.2 km. The height of cloud-top level z_{ct} is ~14.2 km; D_a is estimated as $c \times (z_{ct} - z_{lfc})$. A value of 0.75 for c is used to indicate the depth where the adiabatic maximum upward motion occurred within the storm. The CAPE is 2022 J kg^{-1}. From (2.8), $D_d = 0.5D_a$ (~4875 m) for $z_{ct} = 14200$ m, $t_{p(\min)} = 600$ s, and $t_{p(\max)} = 1200$ s. The above minimum and maximum parcel residence times are suggested to be typical in certain convective cloud systems (e.g., Cotton and Anthes 1989) and thus should be used only if no other means to determine them is available. In other words, better parcel residence times (if available) within the specific thunderstorms to be analyzed can help refine the criteria further. Using (2.2), W_a is ~55 m s^{-1} for $W_{lfc} = 3$ m s^{-1}. Using (2.9), d is ~0.15. Now, using (2.4) the threshold updraft W_d is ~8 m s^{-1}. The above-determined values for D_d and W_d are in general agreement with the parameters listed in Table 1.

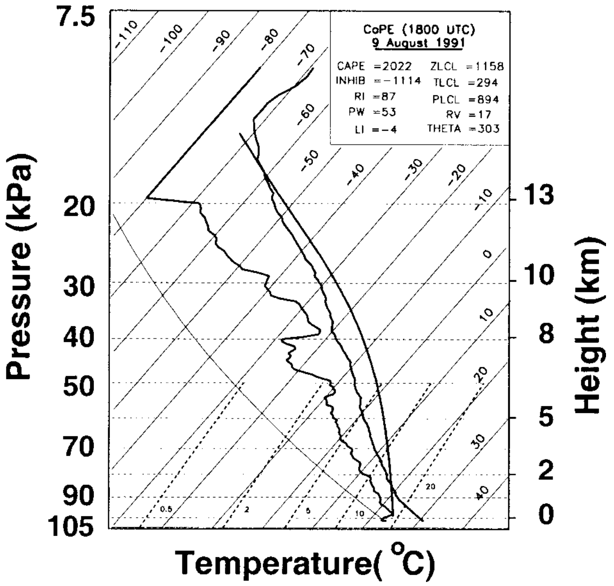

FIG. 2. Composite sounding representative of the prestorm conditions for the 9 Aug 1991 CaPE day.

3. Convective cells within the storm

The multicell thunderstorm observed on 9 August 1991 in the Doppler radar coverage area of the CaPE experiment was analyzed to understand its convective cell evolution using high-resolution velocity data from three Doppler radars (Stalker 1997). The storm contained several coexisting convective cells during a 44-min analysis period. Because of the simultaneous existence of several convective cells within the storm, many known cell interactions potentially may have influenced the overall organization of the storm. Since cell interactions were critical in the organization of the storm, an objective method to identify each and every cell through out the lifetime of the storm is imperative. Using the method developed in this note, the storm is shown to have been organized into two cell complexes (or clusters) in the early stage. During the later stages of the storm, the storm growth was dominated by merging of mature cells with the new cells formed in the region between the two complexes.

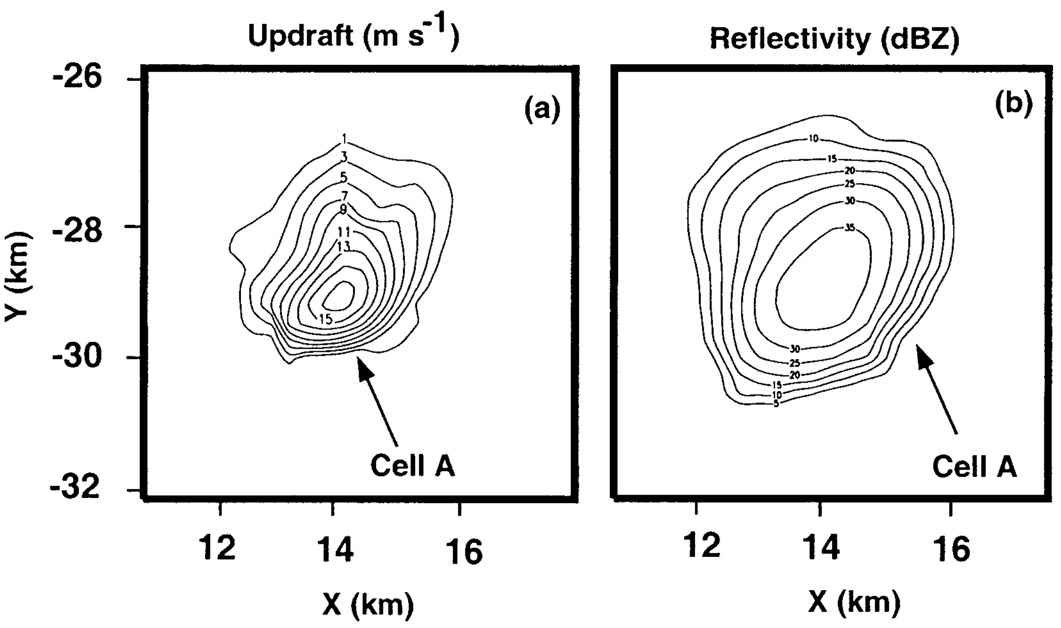

FIG. 3. (a) Horizontal cross section of updraft in cell A′ at 1755 UTC (contours start from 1 m s^{-1} with an increment of 2 m s^{-1}). (b) Horizontal cross section of corresponding reflectivity field (Z) starting from 5 dBZ with an increment of 5 dB. Cross sections are shown at 5.8 km above ground level and the coordinates are relative to CP-2 radar.

The first convective cell (A) is identified in complex 1 using the parameters given in Table 1 at 1755 UTC. Since this cell formed earlier than the analysis time of 1755 UTC, it is renamed cell A′ to indicate its mature growth stage based on the cell naming procedure discussed in section 2d. At the next analysis time of 1801 UTC, two other cells (B and C) are identified in complex 1. Cell A was the dominant cell in complex 1 and is shown in Fig. 3. Four new cells (D, E, F, and G) are identified at 1803 UTC in complex 2 located to the northwest of complex 1 (see Fig. 4). In complex 2, cells D and E were better organized than cells F and G. Cells

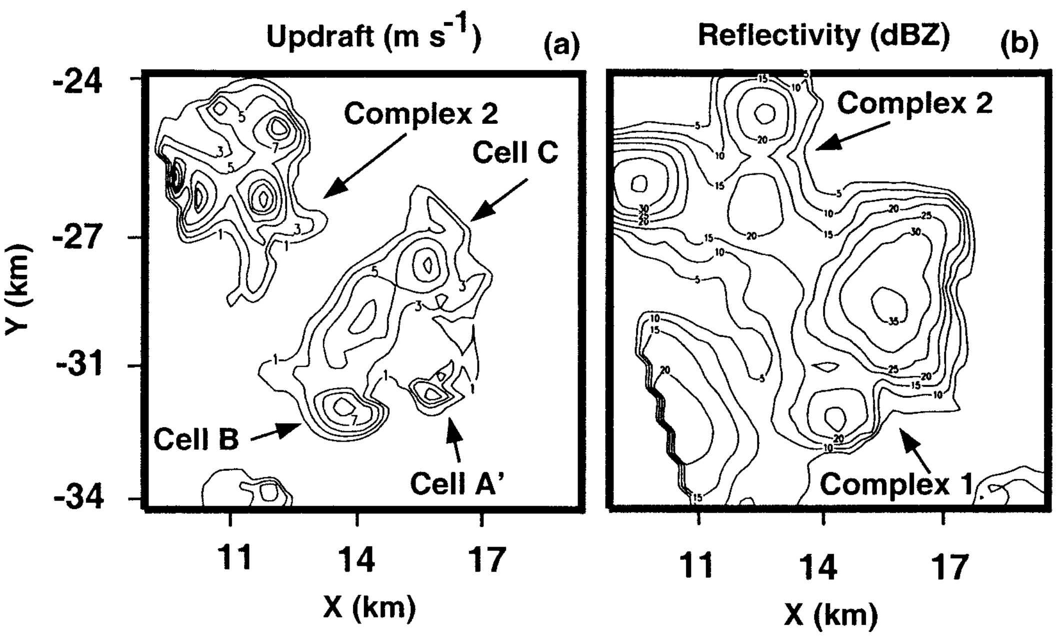

FIG. 4. (a) Horizontal cross section of updraft in cells A′, B, and C of complex 1 and in cells D, E, F, and G of complex 2 at 1803 UTC (contours start from 1 m s^{-1} with an increment of 2 m s^{-1}). (b) Horizontal cross section of corresponding reflectivity field (Z). Cross sections are shown at 5.8 km above ground level and the coordinates are relative to CP-2 radar.

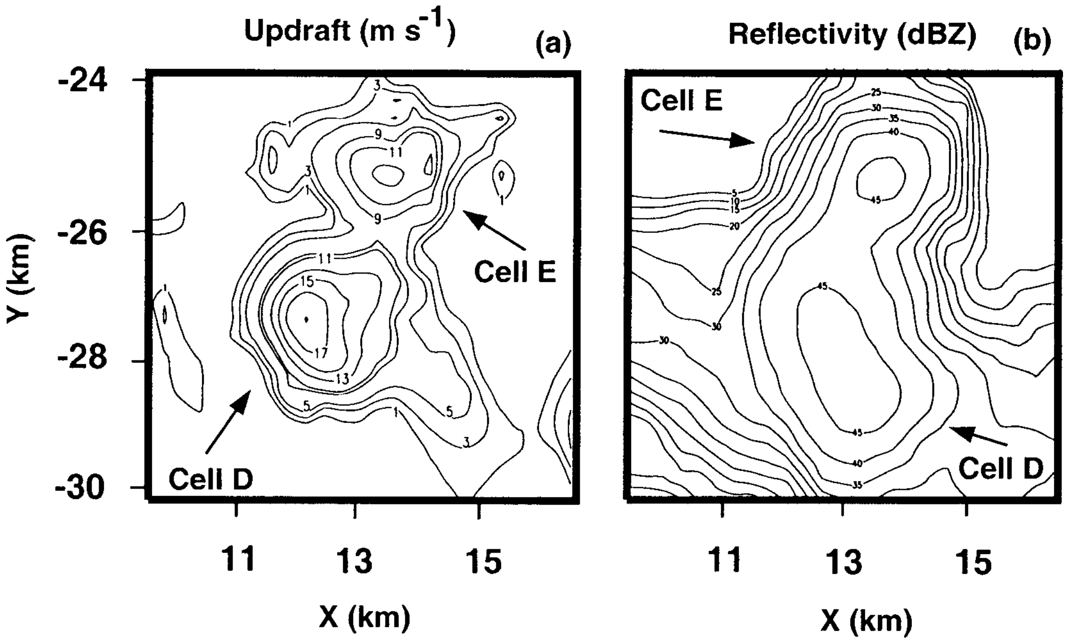

FIG. 5. (a) Horizontal cross section of updrafts in cells D and E of complex 2 at 1808 UTC (contours start from 1 m s^{-1} with an increment of 2 m s^{-1}). (b) Horizontal cross section of corresponding reflectivity field (Z). Cross sections are shown at 5.8 km above ground level and the coordinates are relative to CP-2 radar.

D and E are shown using horizontal cross sections of updraft (Fig. 5a) and reflectivity (Fig. 5b) to further illustrate their organization. Cells F and G were rather short lived and dissipated by 1808 UTC.

At 1808 UTC, cell B′ entered the dissipating stage. Also by this time, cell A′ completely dissipated. Two minutes later at 1810 UTC, cells D and E entered the mature stage. See Table 2 for an overview of the cell characteristics of the dominant cells (A, D, and E) within the storm. By satisfying the objective criteria, a total of 15 convective cells are identified during the entire analysis period. We have tabulated all convective cells identified with the corresponding time at which they are first identified (see Table 3). It is important to note that other previous studies using a more conventional method did not identify as many convective cells within the storm (e.g., Bringi et al. 1997). This method is arguably an important step toward understanding convective cell interactions and their merging behavior. It is also important to note, however, that 6 of the 15 cells were rather short lived while the remaining cells were active for more than 10 min. Cells named by those letters hyphenated with the letter ''m'' (-m) are identified in the region between the two complexes and/or are considered to have resulted from new cell growth known as secondary cell growth. Secondary cell growth can occur due to many processes, for example, when the outflows resulting from downdrafts of two interacting cells collide (Simpson 1980). The transient nature of some of the six short-lived cells may be attributed, for example, to the suppressing effects of adjacent larger cells mentioned in previous studies on cell interactions (e.g., Hill 1974; Wilkins et al. 1976). For further information on the storm morphology, the reader is referred to Bringi et al. (1997) who illustrated a detailed structure of the storm. The raw radar data were originally processed for Bringi et al. (1997) who included details on the retrieval techniques used.

4. Summary and discussion

We have presented a method to define and identify significant convective cells in multicell thunderstorms by developing four generalized objective criteria. These

TABLE 2. Cell characteristics of three prominent cells.

		Cell characteristics		
Cell name	Time identified (UTC)	Peak updraft (m s^{-1})	Updraft area (km^2)	Cloud top (km, AGL)
A	1755	18.0	8.0	8.0
D	1803	18.0	9.0	9.0
E	1803	16.0	3.5	9.25

TABLE 3. Chronological designations of all identified cells. Cell names hyphenated with the letter ''m'' (-m) are secondary cells.

Number	Cell name	Time identified (UTC)
1	A	1755
2	B	1801
3	C*	1801
4	D	1803
5	E	1803
6	F*	1803
7	G*	1803
8	H	1810
9	I-m	1810
10	J-m	1810
11	K-m	1814
12	L*	1817
13	M*	1824
14	N*	1828
15	O	1830

* Short-lived cells.

criteria have been extended based upon four parameters found adequate in identifying many prominent convective cells of the 9 August 1991 CaPE multicell storm. The thresholds for the generalized criteria are chosen from a representative proximity sounding using the air parcel theory.

The first criterion states that a threshold updraft (W_d) must develop within a cell to produce precipitation against the diluting effects of the environment. The second criterion states that a cell must develop to a threshold cloud-layer depth (D_d) to ensure a minimum parcel residence time for precipitating convection. The third criterion requires that a threshold updraft area (A_d) develop at the threshold cloud-layer height (H_d). This criterion is important for two reasons. First, it assures a minimum upward mass flux at the threshold cloud-layer height. Second, it eliminates spuriously identified cells resulting from interpolation of raw radar data to a finer Cartesian grid. The fourth criterion states that all cells must originate within the PBL. This criterion is desirable as it assures that when a cell is first identified it is in its convective growth stage. Cells that may originate at upper levels (e.g., due to updraft collisions) are not accounted for in this method. Also cells that are confined to a shallow cloud layer near cloud base (e.g., cumulus cells) are excluded in this method.

Methods currently available for identifying all convective cells within multicell thunderstorms in understanding how adjacent cells interact and merge into larger cells are limited. One of the limitations, for example, is the lack of information about the height at which a convective cell should be identified. Other issues include the storm stage at which cells must be identified, what variables (e.g., vertical motion, reflectivity, or even total lightning) are required, and finally what thresholds are appropriate for the above variables. The method presented in this note provides insight into the above issues. For example, convective cell identification should begin when a cell is in its growth stage. Cell identification during the growth stage can be accomplished using any existing reflectivity-based method. However, reflectivity-based methods become less useful beyond the convective growth stage when reflectivity and updraft cores may exhibit poor correlation. In addition, our method estimates the thresholds of updraft and the level at which to define and identify convective cells during the entire lifetime.

If efficient microphysical processes (e.g., warm rain process due to particle collision and coalescence or ice-phase processes) are known to exist within a multicell thunderstorm, D_d may be further adjusted. In other words, 4.9 km for D_d may be slightly overestimated for the storm since the collision–coalescence process was shown to be active within the storm (Bringi et al. 1997). From the standpoint of ice-phase microphysics, D_d may also indicate whether a cell should contain a cold cloud layer (with temperatures below 0°C) for effective production of precipitation.

Acknowledgments. This research was supported by the National Science Foundation under Grants ATM-9200667 and ATM-97-04547 and partly by NOAA sponsorship of the Southeast Consortium on Severe Thunderstorms and Tornadoes, via Contract 92-1230-03 from North Carolina State University. Dr. James Stalker acknowledges helpful discussions with many colleagues, especially Drs. James Bossert and Jon Reisner. We also thank the three anonymous reviewers whose valuable suggestions immensely improved the manuscript. This manuscript was produced using the resources at LANL within the Atmospheric and Climate Sciences Group of the Earth and Environmental Sciences Division. LANL is operated by the University of California for the Department of Energy.

APPENDIX

List of Symbols

Symbol	Definition (units)
A_d	Threshold updraft area (km^2)
c	Fraction of CAPE up to z_{max} (nondimensional)
d	Dilution coefficient (nondimensional)
D_a	Adiabatic cloud-layer depth (m)
D_d	Threshold cloud-layer depth (m)
Δx	Grid spacing of the interpolated data (m)
dz	Elemental depth (m)
H_a	Adiabatic cloud-layer height (m)
H_d	Threshold cloud-layer height (m)
ρ	Air density (kg m^{-3})
T_a	Adiabatic parcel temperature (K)
T_e	Environmental temperature (K)
$t_{p(a)}$	Adiabatic parcel residence time (s)
$t_{p(d)}$	Actual parcel residence time (s)

$t_{p(\max)}$ Maximum parcel residence time (s)
$t_{p(\min)}$ Minimum parcel residence time (s)
W_a Adiabatic updraft (m s^{-1})
W_d Threshold diluted updraft (m s^{-1})
W_{lfc} Updraft at the level of free convection (m s^{-1})
W_{pbl} Minimum updraft within PBL (m s^{-1})
Z Radar reflectivity (dBZ)
z_{ct} Cloud-top height (m)
z_{lfc} Height of the level of free convection (m)
$z_{\max}$ Height where upward motion reaches a maximum (m)

REFERENCES

Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment. Part I. *J. Atmos. Sci.,* **31,** 674–701.

Bringi, V. N., K. R. Knupp, A. Detwiler, L. Liu, and R. A. Black, 1997: Evolution of a Florida thunderstorm during the Convection and Precipitation/Electrification Experiment: The case of 9 August 1991. *Mon. Wea. Rev.,* **125,** 2131–2160.

Byers, H. R., and R. R. Braham, 1949: *The Thunderstorm Project.* U.S. Government Printing Office, Washington, DC, 287 pp.

Cotton, W. R., and R. A. Anthes, 1989: *Storm and Cloud Dynamics.* International Geophysics Series, Vol. 44, Academic Press, 883 pp.

Foote, G. B., 1985: Aspects of cumulonimbus classification relevant to the hail problem. *J. Rech. Atmos.,* **19,** 61–74.

Hill, G. E., 1974: Factors controlling the size and spacing of cumulus clouds as revealed by numerical experiments. *J. Atmos. Sci.,* **31,** 646–673.

Houze, R. A., 1993: *Cloud Dynamics.* International Geophysics Series, Vol. 53, Academic Press, 573 pp.

Knupp, K. R., 1988: Downdrafts within high plains cumulonimbi. Part II: Dynamics and thermodynamics. *J. Atmos. Sci.,* **45,** 3965–3982.

Rogers, R. R., and M. K. Yau, 1991: *A Short Course in Cloud Physics.* International Series in Natural Philosophy, Vol. 113, Pergamon Press, 293 pp.

Simpson, J., 1971: On cumulus entrainment and one-dimensional models. *J. Atmos. Sci.,* **28,** 449–455.

——, 1980: Downdrafts as linkages in dynamic cumulus seeding effects. *J. Appl. Meteor.,* **19,** 477–487.

——, N. W. Westcott, R. J. Clerman, and R. A. Pielke, 1980: On cumulus mergers. *Arch. Meteor. Geophys. Bioklim.,* **29A,** 1–40.

Srivastava, R. C., 1985: A simple model of evaporatively driven downdraft application to microburst downdraft. *J. Atmos. Sci.,* **42,** 1004–1023.

——, 1987: A model of intense downdrafts driven by the melting and evaporation of precipitation. *J. Atmos. Sci.,* **44,** 1752–1773.

Stalker, J. R., 1997: Deep convection in a low-shear subtropical environment: Cell interactions and merger processes. Ph.D. dissertation, University of Alabama in Huntsville, 184 pp.

Wilkins, E. M., Y. K. Sasaki, G. E. Gerber, and W. H. Chaplin Jr., 1976: Numerical simulation of lateral interactions between buoyant clouds. *J. Atmos. Sci.,* **33,** 1321–1329.

Yuter, S. E., and R. A. Houze, 1995: Three-dimensional kinematic and microphysical evolution of Florida cumulonimbus. Part I: Spatial distribution of updrafts, downdrafts, and precipitation. *Mon. Wea. Rev.,* **123,** 1921–1940.