Electrification and Lightning in an Idealized Boundary-Crossing Supercell Simulation of 2 June 1995*

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ABSTRACT

A nonhydrostatic cloud model with electrification and lightning processes was utilized to investigate how simulated supercell thunderstorms respond when they move into environments favorable for storm intensification. One model simulation was initialized with an idealized horizontally varying environment, characteristic of that observed across an outflow boundary in the west Texas Panhandle on 2 June 1995 with larger convective available potential energy (CAPE) and wind shear on the boundary's cool side. That simulation was compared with a control simulation initialized without the boundary. The simulated right-moving supercell rapidly increased in updraft strength and volume, low-level rotation, radar reflectivity, and 40-dBZ echo-top height as it crossed the boundary, whereas the supercell that did not cross the boundary failed to intensify. For the same kinematic and microphysical evolution and the same inductive charging parameterization, four noninductive (NI) charging parameterizations were tested. In all four cases, there was a general tendency for the charge regions to be lofted higher within the updraft after crossing the boundary. Once the precipitation regions between the main storm and a secondary storm started merging farther on the cool side of the boundary, a gradual deepening and strengthening of the lowest charge regions occurred with relatively large increases in hail and graupel volume, charging rates, charge volume, charge density, and intracloud and cloud-to-ground (CG) flash rates. The negative charge present on graupel within the downdraft appeared to have a common origin via strong NI charging within the midlevel updraft in all four NI cases. Positive channels were more consistent in coming closer to the ground with time compared to negative channels within this graupel and hail-filled downdraft (four of four cases). Those NI schemes that also set up a positive dipole (three of four cases) or inverted tripole (two of four cases) above the downdraft had downward-propagating positive channels that reached ground as positive CG (+CG) flashes. The best overall performance relative to the 2 June 1995 CG lightning observations occurred within one of the rime-accretion-rate-based schemes and the Gardiner scheme as parameterized by Ziegler.

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1. Introduction

On 2 June 1995, a significant outbreak of 20 long-lived supercell thunderstorms struck the west Texas Panhandle. During the severe weather outbreak, 11 of the 20 analyzed supercell storms crossed a preexisting outflow boundary (Gilmore and Wicker 2002, hereafter GW02). In addition to being more likely to produce tornadoes (Rasmussen et al. 2000), boundary-crossing storms unambiguously increased in low-level rotation (9 of 11 cases) and production of positive cloud-to-ground (+CG) lightning flashes (5 of 11 cases) within 60 min of crossing the boundary regardless of their initial dominant polarity (GW02). (+CG flashes effectively bring positive charge to ground, while –CG flashes bring negative charge to ground.) Storms also unambiguously increased in radar reflectivity *immediately* after crossing the boundary in 5 of 7 cases where the boundary-crossing time could be precisely identified (and possibly as many as 9 of 11 cases if including storms with less precise boundary-crossing times). Boundary-crossing storms produced +CG flashes in close association with descending cores of reflectivity >60 dBZ in 5 of 7 cases and a majority of +CG flashes occurred in base scan reflectivity >50 dBZ (GW02).

The study described herein involves simulated boundary-crossing supercells with a nonhydrostatic thunderstorm model. The environments on either side of the boundary were based upon those observed on 2 June 1995 by the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) field program (Rasmussen et al. 1994). Results from the simulations were used to relate the local environment to storm kinematic structure, hydrometeor distribution, charge structure, and dominant CG lightning polarity¹ to better understand the actual supercell behavior on 2 June 1995. The simulation results herein improve upon those from Gilmore and Wicker (1998) and Gilmore et al. (2002) in that the numerical cloud model incorporates more sophisticated microphysics (Straka and Mansell 2005), electrification (Mansell et al. 2005, hereafter M05), and a lightning parameterization (Mansell et al. 2002). In the following section, a brief chronological review of the most recent results and hypotheses from observational and modeling studies will be presented to motivate our research questions.

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¹ GW02 defined positive (negative) CG dominant polarity as a time when the 5-min +CG (–CG) flash rate exceeded the 5-min –CG (+CG) flash rate.

2. Chronological summary of related previous studies

a. Observational studies

Although most severe storms in the United States predominantly produce –CG flashes (e.g., Carey et al. 2003), storms that produce either a low –CG flash rate (MacGorman et al. 1989; Perez et al. 1997; Lang et al. 2000; McCaul et al. 2002) or a predominantly +CG flash rate (Reap and MacGorman 1989; Stolzenburg 1994; Carey et al. 2003) are commonly found to also be severe. From a large sample, a greater positive flash rate is positively correlated to stronger tornadoes and larger hail reports (Carey et al. 2003) produced by presumably stronger updrafts. Lang and Rutledge (2002) found that predominantly positive CG storms tend to produce much larger volumes of 10 and 20 m s^{–1} updraft and larger amounts of precipitation (both hail and rain as observed from polarimetric radar) than produced by low –CG flash rate storms. These studies suggest a relationship between storm updraft strength, microphysics, and electrification.

As the kinematic state of a storm changes, so can its microphysics and lightning behavior. MacGorman et al. (1989) and Lang et al. (2000) observed that the intracloud (IC) flash rate in the mesocyclone region peaked when the storm was most intense and the CG flash rate was low. MacGorman et al. (1989) suggested that the stronger updrafts lofted the charge regions at that time thereby reducing the –CG flash rate. Similarly, Wiens et al. (2005) found that increases in graupel echo volume and total flash rate were closely correlated to increases in updraft volume. Wiens et al. (2005) also correlated higher +CG flash rates to the formation and descent of hail consistent with earlier observations by Carey and Rutledge (1998). Many studies (e.g., Rust et al. 1981; MacGorman et al. 1989; Williams 1989; Changnon 1992) have also shown that the largest –CG flash rates were usually associated with the descent of large reflectivity cores (particularly the >55 dBZ core).

Numerous studies have reported the local intensification of supercell thunderstorms as they cross outflow boundaries (e.g., Maddox et al. 1980; Wakimoto and Atkins 1996; Markowski et al. 1998). For the 2 June 1995 case, Rasmussen et al. (2000) and GW02 documented the presence and possible role of larger convective available potential energy (CAPE), boundary layer water vapor mixing ratio, and low-level shear present on the immediate cool side of the outflow boundary. Rasmussen et al. (2000) and GW02 showed that while both environments supported supercells with midlevel mesocyclones, the environment on the imme-

diate cool side (within 40 km) of the mesoscale outflow boundary was associated with tornadic supercells with stronger low-level mesocyclones. Rasmussen et al. (2000) hypothesized that horizontal vorticity enhancement associated with the baroclinic zone on the cool side of the boundary was the key factor for enhancing the low-level (1–3 km AGL) rotation after significant tilting and stretching by storm-scale processes.

For the 2 June case, there were no observations of the IC flashes or charge structure (W. D. Rust 2000, personal communication). GW02 analyzed CG flash observations from the National Lightning Detection Network (NLDN) and correlated these in time and space with Weather Surveillance Radar-1988 Doppler (WSR-88D) radar data and storm reports. After storms crossed the boundary, large increases in +CG flash rates were associated in close time–space proximity with descending precipitation cores (radar reflectivity exceeding 60 dBZ) with the majority of +CG flashes occurring within the 50-dBZ base scan contour (GW02). In contrast, storms that did not cross the boundary (called “warm side storms” by GW02) tended to be dominated by –CG flashes. Many storms remained isolated while other storms (particularly on the boundary’s cool side) moved close enough to merge in portions of their radar reflectivity regions for a period—thereby likely influencing one another (Gilmore 2000; GW02). Following the observational hypothesis of MacGorman and Nielsen (1991), GW02 suggested that the source of positive charge for some of the +CG flashes in enhanced +CG storms might have had an enhanced lower positive charge region. GW02 further hypothesized for the 2 June 1995 case that many of the storms exhibited an increase in +CG flashes after crossing the boundary due to the associated increase in liquid cloud water content (CWC) and updraft temperature that resulted from the ingestion of larger boundary layer water vapor mixing ratio and equivalent potential temperature (θ_e) observed there. Using proximity soundings and the Saunders and Peck (1998) charging diagram, GW02 argued that enhanced noninductive (NI) positive charging of graupel/hail descending to lower levels would deepen and strengthen the positive charge region lower in the cloud thereby providing a source of positive charge and enhancing the probability of +CG flashes there.² GW02 also argued that the stronger storm would have a corresponding stronger upper positive charge region on ice crystals in the anvil and acknowl-

edged that positive channels could descend from a higher-altitude positive charge region farther down-shear as well (GW02’s Fig. 8). Indeed, a significant minority of the total +CG flashes in some cases also occurred farther downstream/downshear of the mesocyclone in a region of moderate base-scan reflectivity (Gilmore 2000). Furthermore, GW02 followed the hypothesis of MacGorman et al. (1989) that a strengthening updraft would loft the main negative graupel-charging region making –CG flashes less likely. In contrast, storms that did not cross the boundary did not experience +CG flash increases and tended to be dominated by –CG flashes.

b. Modeling studies of the 2 June case

Gilmore and Wicker (1998) and Gilmore (2000) simulated supercells within a homogeneous environment representative of the boundary’s cool side from 2 June 1995 and found much stronger low-level mesocyclones and updrafts as a direct consequence of larger low-level shear and CAPE compared to a homogeneous simulation using an environment representative of the warm side. Gilmore et al. (2002) then used both soundings to initialize a heterogeneous environment with an idealized boundary. Simulated supercells crossed the boundary and increased in updraft temperature, speed, and CWC, strengthened in low-level mesocyclone rotation, and increased in diagnosed hail/graupel-charging rate. These increases were consistent with larger environmental CAPE, boundary layer moisture, and low-level vertical wind shear on the immediate cool side of the boundary. Both Gilmore and Wicker (1998) and Gilmore et al. (2002) used Lin et al. (1983)–like microphysics with three ice and two liquid categories. Although Gilmore et al. (2002) diagnosed NI charging rates, they did not include any prognostic charge, lightning, or inductive charging parameterizations.

3. Experimental methodology

a. General overview

This study herein improves upon previous works of simulated boundary-crossing supercells by using the Mansell et al. (2002) lightning parameterization and the Straka and Mansell (2005) microphysics to obtain a better quantitative description of the role of the environment upon storm kinematics, microphysics, NI and inductive charging, development of the charge regions, and thunderstorm lightning activity. This work is also part of a larger effort to evaluate the flash performance associated with each NI charging parameterization scheme (to be described in section 3b) against observed

² Others have also found an association between +CG flashes and enhanced positive noninductive charging of graupel in high liquid water content conditions (MacGorman et al. 2002; Carey et al. 2003).

flash behavior in many types of thunderstorm environments. The 2 June case study was a particularly interesting test bed because of the apparent dominant CG polarity dependence upon the local environmental conditions (GW02); a successful simulation would need a NI scheme associated with $-$ CG flashes in weaker storms as well as increasing in $+$ CG flashes in intensifying storms. Sensitivity experiments (below) were designed to assess the capability of the model in simulating characteristics of the observed 2 June 1995 storms and to answer specific research questions motivated from the observational hypotheses of GW02.

1) OBJECTIVES OF THE NI SCHEME SENSITIVITY TESTS

The first objective was to determine whether any of the four NI charging schemes (see critical curves in Fig. 1) would produce CG lightning behavior consistent with the observed storms documented in GW02. The second objective was to compare the different charge structures and evolutions resulting from each NI charging scheme and specifically address the following questions:

- What was the relationship between hydrometeor structure, charge structure, and CG flash rate in each NI scheme and how did they differ?
- Which of the charge regions in the simulated storms were mainly attributed to NI charging? Which were mainly attributed to inductive charging?
- How did the charge structure evolve for each NI scheme?

2) OBJECTIVES OF THE BOUNDARY TESTS

The homogeneous environment simulation was compared to its corresponding heterogeneous environment simulation for each of the NI schemes. The homogeneous simulation was intended to simulate a storm similar to the numerous warm-side storms that never crossed the boundary on 2 June 1995 while the heterogeneous environment simulation was intended to represent those storms that did cross the boundary. The first objective of the boundary tests was to determine qualitatively and quantitatively how a supercell thunderstorm responds kinematically and microphysically as it crosses a boundary into a new environment favorable for storm intensification. The second objective was to test how these changes influence storm electrification and lightning. Specific research questions, motivated from GW02 observational hypotheses, were as follows:

- Do storms need to reach a particular microphysical maturity before they are capable of generating large

FIG. 1. Respective critical curve diagrams of (a) the G85 NI scheme adapted by Ziegler et al. (1991), (b) the Saunders et al. (1991) NI scheme as modified by Brooks et al. (1997) and Helsdon et al. (2001), and (c) the Saunders and Peck (1998) and RR (M05) NI schemes. The SP98 critical curve used for this study was modified by M05 and is shown here by "Modified SP98." The charging sign (+ or $-$) acquired by graupel is shown for each region and zero charging is indicated with "0." Charging sign and magnitude for each scheme for T colder than -30°C are extrapolated from the laboratory experiments (right of dashed line) following M05. CWC, EW, and RAR have been defined in the text.

$+$ CG flash rates on the cool side of the boundary? If so, how does the precipitation structure evolve?

- Are descending reflectivity cores, filled with graupel and hail produced during the intense updraft phase (after crossing the boundary), collocated in space and time with increased $+$ CG flash rates? If so, why?

b. Model charging, lightning, and microphysics schemes

Electrification via NI charging occurs when riming graupel pellets collide with ice crystals in the presence

of supercooled liquid cloud water (Takahashi 1978; Gardiner 1985; Ziegler et al. 1991; Saunders et al. 1991; Saunders and Peck 1998). (Complete details of the model parameterizations of charge separation and ion processes can be found in M05.) In this study, the following four NI charging parameterization schemes were tested: Gardiner et al. (1985, hereafter G85 and called GZ by M05) modified following Ziegler et al. (1991), Saunders et al. (1991, hereafter S91) modified following Helsdon et al. (2001), Saunders and Peck (1998, hereafter SP98) modified following M05, and the riming rate (RR; M05). The Takahashi (1978) scheme was omitted from the analysis herein because, in our earlier tests (not shown) and in much more extensive tests shown in M05, it produced exclusively $-CG$ flashes thereby making it an unlikely candidate for testing the observational hypotheses requiring $+CG$ flashes in the study herein. In general for NI charging, graupel acquires a positive charge at higher cloud temperatures ($T > -10^{\circ}C$), provided that CWC is not too low (see Fig. 1). Critical curves in Fig. 1 delineate between the cloud conditions where graupel can acquire positive charge or negative charge during a single graupel-ice collision. The sign and amount of charge separated differs between the schemes (Fig. 1, not shown for magnitudes). These can probably be attributed to differences in the laboratory apparatus' controlling the cloud conditions (e.g., Saunders et al. 2003) as well as the choice and number of dependent variables describing the cloud crystals and droplets (Fig. 1). For instance, while G85 is parameterized with CWC, S91 considers the collection efficiency between graupel and cloud water to obtain an effective CWC (abbreviated as EW), and RR/SP98 additionally multiplies EW by the differential velocity between the graupel and cloud droplets ($EW \times V$) to obtain a riming accretion rate (RAR).

Electrification via inductive charging occurs when hail and graupel experience rebounding collisions with cloud water in the presence of an electric field (e.g., see theoretical and modeling results in Aufdermaur and Johnson 1972; Paluch and Sartor 1973; Chiu 1978; Gaskell 1981; Ziegler et al. 1991; Brooks and Saunders 1994). The inductive charging strength in the model that was used is determined by the rebound probability (E_r) and the average cosine of the angle of rebounding collision ($\langle \cos \theta \rangle$) between the cloud droplet and graupel/hail particles (Ziegler et al. 1991). Coefficients used for inductive graupel-droplet charging were the same for all simulations ($E_r = 0.01$ and $\langle \cos \theta \rangle = 0.5$), and are between the "moderate" to "strong" values presented in M05, which ranged from $E_r = 0.007$ to 0.015 and $\langle \cos \theta \rangle = 0.2$ to 0.50 . In the experiments herein, al-

though only one set of inductive settings is used, the inductive charging did vary in magnitude between the four NI cases because inductive charging is a function of the local electric field produced by the existing charges from all charging mechanisms. Inductive charging seems to have an overall dissipative effect (weakening the electric fields that would otherwise be present) when using "weak" values from Ziegler et al. (1991) or moderate values from M05. Also, the default minimum ice concentration of 1 L^{-1} (Straka and Mansell 2005) was used in all experiments. M05 have shown that as the minimum ice concentration is increased, more charge is separated due to increased collisions, and more IC flashes result.

The default parameters for microphysical species (Straka and Mansell 2005) were used for all simulations, and the microphysical evolution is the same for each NI charging experiment. The electrification does not feed back to alter the dynamics or the microphysics in order to maintain the same dynamic/microphysical conditions for each simulation; such allows an easier comparison between simulations made with different NI charging parameterization schemes. Properties of "graupel" (such as mixing ratio and amount/sign of charge carried) in the current study refer to the sum total of the three separate graupel categories of the microphysics scheme. Furthermore, similar properties for "hail" refer to the sum total of the two separate high-density hail categories and the single frozen drop category. The microphysics scheme also has cloud droplets, rainwater, and four additional ice species (column and plate ice crystals, rimed cloud ice, and snow aggregates).

Lightning flashes were parameterized with the Mansell et al. (2002) three-dimensional branched lightning model. Bidirectional channels (with positive charge on one end and negative on the other) are propagated in a stochastic step-by-step fashion on a regular grid. The IC flashes, by definition, do not reach ground. If the positive (negative) channel branch reaches ground, defined as the lowest model grid level, the flash behaves as and is classified as $+CG$ ($-CG$). The lightning model includes the necessary physics for channels to reach ground on their own. However, Mansell et al. (2002) found that channel propagation stopped near ground in some cases due to a numerical artifact that results owing to coarse model grid spacing. Because most flashes that come within 1 or 2 km of ground tend to come to ground (P. Krehbiel 2002, personal communication), the Mansell et al. (2002) parameterization automatically brings to ground any channels that propagate down below a threshold altitude, which in

this study was set at 2.2 km AGL. The model does not account for transient processes such as multiple return strokes and the stepped-leader breakdown process for CG flashes, or the leader/recoil streamer processes for IC flashes.

c. Model initialization and environments

All simulations were carried out for 4 h in a $(x, y, z) = (191, 125, 22)$ km domain with a horizontal grid length of $\Delta x = \Delta y = 1200$ m for the dynamics/microphysics ($\Delta x = \Delta y = 600$ m for the lightning propagation) corresponding to 159×104 grid points (319×209 grid points). A stretched 51-point vertical grid was used with finer grid spacing near the ground ($\Delta z = 100$ m near the surface stretched to 600 m at and above 7 km AGL).

The simulation with the heterogeneous environment (with the boundary) was initialized with two soundings (see Fig. 2a), while the simulation with the homogeneous environment was initialized with only one of the two soundings (the “warm side”). For the heterogeneous initialization, a smooth horizontal variation between the warm side and “cool side” environments was applied by using an inverse hyperbolic tangent function whereby 90% of the change between environments occurred over a 14-km distance (as in Gilmore et al. 2002). The maximum change between environments occurred at $x = 125$ km. The variation was applied only below $z = 2.4$ km where important differences were observed between soundings (Rasmussen et al. 2000; GW02). Above $z = 2.4$ km, the warm side sounding was used. Additionally, both wind profiles were rotated by 45° so that the northwest–southeast boundary became parallel to the model’s y axis. A northwest–southeast boundary orientation was similar to that observed near the Dimmitt and Sunnyside, Texas, boundary-crossing storms of 2 June 1995.

The warm side sounding used in the initialization was a composite of two soundings from the warm side of the actual 2 June 1995 boundary. The 2058 UTC Hub, Texas, thermodynamic profile was closest in location to storm initiation on 2 June 1995 and was the most unstable of all warm side soundings (but not as moist and unstable as the cool side). To obtain longer-lived storms, the sounding was lifted adiabatically 300 m near the capping inversion to reduce the convective inhibition (CIN) following Gilmore and Wicker (1998), and the Hub winds were replaced with those from the 2315 UTC Lubbock, Texas, sounding below $z = 1.9$ km thereby providing enhanced low-level shear and storm-relative helicity. The resulting supercells were longer lived. Additionally, in order to suppress both secondary

FIG. 2. (a) Skew T -log p diagrams and (b) hodographs used to define the initial conditions on the warm (gray dashed line) and cool (black line) sides of the boundary. Both hodographs and soundings used in the initialization are identical to the Hub, TX, sounding above $z = 2.4$ km AGL (see GW02 for the upper-level thermodynamic profile). Hodograph pressure levels are indicated with black dots every 100 hPa and are labeled every 200 hPa. The large circle (square) shows the ground relative velocity of the storm R1 while on the warm (cool) side of the boundary (prior to the reflectivity merger).

cell development³ and upper-level formation of ambient cirrus cloud, the warm side sounding values of q_v were reduced via trial and error between 1 and 1.95 km (near the LCL) and above 11.5 km, respectively.

The cool side sounding is a modified version of the Lockney, Texas, sounding used in Gilmore et al. (2002) except that initial temperatures between 1250 and 2350 m were increased slightly to increase the CIN. This was

³ Although both isolated and nonisolated storms occurred on 2 June 1995 (Gilmore and Wicker 2002 and Table 1 herein), secondary cells were suppressed with these sounding modifications in an effort to simulate the presumably simpler-to-understand isolated storm case. However, the use of this modified sounding resulted in suppressing only *some* of the secondary storms along the boundary.

found to prevent some of the secondary cell development on the cool side of the boundary compared to the unmodified sounding in test simulations. Lockney was located on the immediate cool side of the boundary and was associated with the greatest low-level shear, CAPE, and low-level moisture of anywhere across the domain (Fig. 2a; see discussion in GW02).

Convection was initiated with a warm thermal bubble with a maximum temperature perturbation of +3 K centered at 1.5 km AGL and with horizontal and vertical radii of 10 and 1.5 km, respectively (similar to Klemm and Wilhelmson 1978). The bubble was initially set at the horizontal coordinates $x = 30$ km and $y = 50$ km (~ 100 km from the boundary) so that the right-moving storm crossed the boundary in about 2 h. Thus, storms were initiated within the warm side environment in both the homogeneous and heterogeneous simulations. The boundary moved SW at an average ground-relative speed of approximately 4 m s^{-1} . The model domain was also translated at $dx/dt = 5.4$ and $dy/dt = 2.0 \text{ m s}^{-1}$ so that the storm would be closer to the center of the domain at maturity.

d. Storm analysis methodologies

The model output was postprocessed by focusing on the data within a storm-following box. Of primary interest was the strongest right-moving storm; the left mover and weaker secondary cells were analyzed separately (not shown). The lateral edges of this box are shown in Fig. 3. Radar reflectivity was diagnosed from the microphysical variables using the methodology of Ferrier (1994), but assuming only dry particles. From this box, statistics such as maxima and totals versus time and height of various model fields were generated. Although the storm-following box initially gathered groups of CG flashes, each CG flash was additionally mapped atop model radar reflectivity to ensure that it was assigned to its correct parent storm.

4. Results

a. Kinematics and microphysics evolution in the homogeneous and heterogeneous environments

The initial evolution in the original right-moving supercell (R1) storm's kinematics and microphysics was similar but not identical in both the homogeneous and heterogeneous cases (Figs. 3–5) prior to the time when the storm crosses the boundary. However, as R1 crossed the boundary near $t = 120$ min (Fig. 3b), it significantly increased in maximum updraft speed at mid and low levels (Fig. 4a), 20 m s^{-1} updraft volume (Fig. 4b), 40-dBZ echo-top height (Fig. 5a), and maxi-

mum low-level rotation (Fig. 4c), which indicated a stronger supercell. GW02 had observed increases in 40-dBZ echo-top height and used these as a proxy for an increasing updraft. The simulated trend in 40-dBZ echo-top height also followed the maximum updraft trend, thereby providing confidence in that previously used observational technique. The midlevel updraft reached its maximum after crossing the boundary and remained sustained for about 40 min (Fig. 4a). Additionally, after crossing, R1 increased in maximum radar reflectivity (Fig. 5a), graupel mixing ratio (Fig. 5b), hail mixing ratio (Fig. 5c), graupel volume (Fig. 5d), and hail volume (Fig. 5e). These quantities increased further after the reflectivity cores for storms R1 and another strong supercell storm (S1) completely merged after R1 crossed the boundary ($t = 205$ min; Fig. 3).

The heterogeneous environment was responsible for the formation of S1 and its later merger with R1 because S1 formed as the low-level outflow from L1/R1 collided with the preexisting boundary. The R1 and S1 updrafts both quickly intensified within the cool side air mass, resulting in relatively fast expansion of their anvils, which began merging at $t = 125$ min (not shown) just after R1 crossed the boundary. The increasing amounts of precipitation mixing ratio merged with time as R1 approached S1 due to different storm motions (Fig. 3). No merger occurred between the respective storm's updraft volumes encompassing the 15 m s^{-1} isosurface (not shown). As the storm precipitation regions continued to merge, graupel/hail mixing ratios and volumes increased through the entire depth of the storm (viz., between $z = 2$ km and $z = 12$ km; Figs. 5b–e). These general increases in graupel/hail mixing ratios and volumes caused larger areas and magnitudes of simulated radar reflectivity at low levels (Figs. 3 and 5a). It is unclear, however, how much of the increase in graupel mixing ratio (and simulated reflectivity) during this time was due to R1's intensification in the higher-CAPE and vertical wind shear environment versus how much of the increase was due to the merging with S1. (Because of this ambiguity, numerous unsuccessful tests with sounding modifications were conducted in an attempt to suppress S1's formation. Nevertheless, it will be shown later that this merger is similar to what occurred for one pair of storms on 2 June 1995.) By $t = 190$ min, both storms had merged in their most intense precipitation core regions (>50 dBZ at $z = 1.5$ km). This period is coincident with particularly large increases in graupel and hail volume (Figs. 5d,e). By $t = 205$ min, the merger appeared to be complete. To capture the merger with S1, the box following R1 was increased by 44% after 205 min (Fig. 3; also see Quick-time animations available in the supplemental mate-

FIG. 3. Simulated radar reflectivity calculated using the Ferrier (1994) technique at $z = 1.5$ km plotted in a ground-relative reference frame for the heterogeneous environment (a) before storm R1 crosses the boundary ($t = 80$ min), (b) after R1 crosses the boundary ($t = 140$ min), and (c) after the reflectivity merger ($t = 205$ min). Also shown is storm reflectivity for the homogeneous environment corresponding to (d) the same time as in (a) ($t = 80$ min), (e) during storm R1's most intense updraft phase ($t = 120$ min), and (f) as R1 dissipates ($t = 155$ min). The black-filled contours represent updraft speeds greater than 15 m s^{-1} at $z = 4.6$ km. The thin black lines are the surface potential temperature perturbation of -1 K relative to the initialization sounding on the warm side of the boundary. The dashed line represents the track of storm R1. The secondary supercell storm that forms on the boundary at $t = 90$ min is labeled S1 and the left-moving supercell storm is labeled L1. The thick NW-SE line bisecting the storm depicts the location of the vertical cross sections shown in other figures herein. Note that the domain is skewed relative to the compass shown in (a) and (d). Color animations can be found in the supplemental material.

rial).⁴ In the homogeneous case, these kinematic and microphysical variables did not experience similar large

⁴ Additional plots of these variables were created with an unchanged box size after 205 min and show that all values vary by $\pm 5\%$ (not shown). Thus, the increases are not artificially related to the increased box size.

increases during R1's temporary intensification phases as shown by selected gray contours in each of the time-height plots (Figs. 4 and 5). Also, in the homogeneous environment, R1 became dominated by low-level outflow and dissipated near 150 min, while the right-moving cell in the heterogeneous environment survived through the 4 h of simulation. Hence, the new environ-

FIG. 4. Time–height contour plots of (a) maximum vertical updraft speed (m s^{-1}), (b) updraft volume greater than 20 m s^{-1} (km^3), and (c) maximum cyclonic vertical vorticity ($\times 10^4 \text{ s}^{-1}$) within a box following storm R1 for the heterogeneous environment (black) and homogeneous environment (gray dashed). Several thin contour lines are shown for the heterogeneous case at regular intervals (marked) with one contour thickened for comparison with a contour from the homogeneous simulation. The comparison contours are (a) 35 m s^{-1} , (b) 10 km^3 , and (c) 150 s^{-1} . In (c), only selected outermost contours are shown. In all plots, the solid vertical line ($t = 120 \text{ min}$) indicates the time when the R1 storm crosses the boundary and the dashed line just prior ($t = 100 \text{ min}$) shows the time when the storm starts to experience the new environment. The last vertical line ($t = 190 \text{ min}$) indicates the time when the reflectivity cores ($>50 \text{ dBZ}$) for storms S1 and R1 merge. The totals (or maxima) for each altitude are computed by evaluating all points in a horizontal plane within the storm-following box. Extrema for the time series are shown in the upper-right corner.

ment in the heterogeneous simulation was critical for intensifying R1 and for sustaining it. In addition, one secondary storm forming on the boundary would later merge with the main supercell. Such an evolution was not possible in the boundary-free (homogeneous environment) simulation. It will be shown later that this merger was an important process in storm electrification and lightning.

The reader may wonder why the R1 storm in the heterogeneous environment began diverging slightly from the homogeneous solution well before crossing the boundary. Small differences in evolution can be seen as early as 25 min (Figs. 4 and 5). The storm in the heterogeneous environment evidently could “sense” the presence of the new environment before crossing the strongest gradient for two possible reasons: 1) the initialization procedure mixed the two environments such that the cool side environment was present to some degree on the warm side of the strongest gradient, and 2) the initialized horizontal pressure gradient induced a weak secondary circulation across the entire domain that enhanced general rising motion thereby destabilizing the warm side of the boundary.

b. Charge structure description in relation to kinematics and microphysics

The evolution of R1 charge structure for the four NI cases are compared in Figs. 6 and 7 by using a common cross-sectional time and location. Because the same kinematic and microphysical evolution is experienced, only the charging and electrification characteristics differentiate the cases. The focus here is on the dominant charge characteristics relevant to CG and IC lightning initiation and propagation and not screening layers or spurious charge regions owing to deposition by lightning. Small to moderate differences in charge magnitudes were found for R1 when the cross section was shifted by a few grid points; however, the dominant charge structures were consistent in sign regardless. Such shifting reveals that the strongest updraft and charge regions slope upward into the page in Figs. 6 and 7. A full appreciation for the charge layers can be achieved by viewing 3D volumetric renderings of charge (not shown). Of interest here is how the charge structure and/or magnitudes changed with time within the regions of main storm updraft, anvil cloud, and below the cloud base for each NI scheme and how these charge structures were related to CG flash initiation. The evolution of the charge structures for each of the NI schemes in the heterogeneous environment will now be described chronologically. These evolutions will then be compared to those in the corresponding homogeneous environment.

At $t = 80 \text{ min}$ (before crossing the boundary, or in the homogeneous case during the most intense updraft at $t = 120 \text{ min}$, Fig. 4a), the SP98 and the RR storms exhibited an inverted tripole (two negative charge regions above and below a main positive one) within the updraft, while the S91 and G85 cases generated a normal tripole (two positive charge regions enclosing a middle negative charge region, Figs. 6a–d and 7a1–d1)

FIG. 5. Time–height contour plots of (a) maximum radar reflectivity (dBZ), (b) maximum graupel mixing ratio (g kg^{-1}), (c) maximum hail mixing ratio (g kg^{-1}), (d) volume (km^3) of graupel exceeding 0.5 g kg^{-1} , and (e) volume (km^3) of hail exceeding 0.1 g kg^{-1} within a box following storm R1 for the heterogeneous environment (black) and R1 for the homogeneous environment

within the updraft. These cross sections were taken just northeast of the updraft maximum (see locations in Fig. 3). These charge structures are similar to the multicell storm charge structure results of M05. Also at $t = 80$ min, regions of low-level negative charge density were found in each case ($y = 85 \text{ km}$, $z = 1\text{--}4 \text{ km}$; Figs. 7a1–d1) *outside the updraft* and beneath the anvil cloud where graupel was falling (Fig. 8a1), the significance of which will be shown later. Although the charge structure in the updraft region was roughly either a tripole or inverted tripole, the graupel-filled downdraft region (as seen in Fig. 8 between $y = 70$ and 85 km) was dominated roughly by a normal dipole (positive above negative) in all four cases at this time.

At $t = 140$ min (after crossing the boundary), a dominant dipolar charge structure was present in the anvil region (in all but RR) and the magnitude of the lower charge region within the updraft (in all but S91) weakened, so that the bottommost charge region (of the tripole or inverted tripole present previously) weakened (Figs. 7a2–d2). This result is consistent with a strengthening updraft lofting the heavier charge-carrying graupel from the lower (5 km) and middle portion (7 km) of the updraft to higher altitude (see 2.5 and 4.5 g kg^{-1} contours in Fig. 5b and similar contours in Fig. 8a2). Lofting also occurred for the lighter ice crystals and snow aggregates mostly residing in the mid-to upper portion of the cloud (not shown). As a result, this general upward movement of charge-carrying particles caused the midlevel charge region (mainly composed of riming graupel) and the upper-level charge region (mainly composed of lighter ice crystals and snow aggregates) to relocate at higher levels (cf. Figs. 7a1–d1 to 7a2–d2). This general upward transport trend of graupel (from 90 to 130 min) was also revealed in upward-sloping graupel mixing ratio and volume aloft (Figs. 5b,d). In contrast, because the updraft of R1 did not strengthen as much in the homogeneous environment (e.g., Figs. 4a,b), enhanced lofting did not occur and the lower charge region remained strong and steady, even during its strongest temporary strengthening phase near $t = 120$ min (Fig. 6). The possible impacts of charge lofting on CG behavior will be discussed in section 4d.

(gray dashed). Several thin contour lines are shown at regular intervals for the heterogeneous case with one contour thickened for comparison with a contour from the homogeneous simulation. The comparison contours are (a) 40 dBZ , (b) 4.5 g kg^{-1} , (c) 4.5 g kg^{-1} , (d) 50 km^3 , and (e) 50 km^3 .

As R1 moved farther northeast of the boundary, the graupel shifted its primary storm-relative fallout region from southeast of R1's updraft to northwest of R1's updraft (Figs. 7e1–e3 and 8), which was a behavior also noticed in the observed boundary-crossing storms analyzed by Gilmore (2000). Perhaps the enhanced southerly wind component (owing to the slower northward storm motion component) shown in Fig. 7e3 enhanced the precipitation fallout to the north side after crossing (Fig. 2b) implying stronger southerly storm-relative environmental wind component between 2 and 6 km. This shifting in fallout was associated with a corresponding shift in storm-relative CG flash location (not shown). Also, this shift was associated with the development of a more extensive downstream anvil region.

At $t = 205$ min (near completion of the merger), the graupel and hail volume increase (Figs. 5d,e) was associated in time with a net charge density increase at all levels (Figs. 7a3–d3) with the largest relative increase occurring at lower levels (primarily observed below 7 km; cf. Figs. 7a2–d2 and 7a3–d3). The merged storm (S1 + R1) charge structure also exhibited a more complex and perhaps more realistic appearance at that time. This is consistent with complex in situ balloon soundings measurements that do not always show a simple charge structure (e.g., Stolzenburg et al. 1998; MacGorman et al. 2005). Furthermore, a net negative charge region was present at $t = 205$ min between $z = 0.5$ and 4 km for all four cases within the downdraft region outside cloud where most of the graupel was falling (Figs. 7a3–d3 and 7e3–f3): similar to that at $t = 80$ min but with a larger volumes of graupel (Fig. 5d) and net negative charge (not shown). The possible importance of this negative charge region on CG behavior will be shown in the next section.

c. Causes of the charge structure in the updraft and downdraft

A Eulerian framework was chosen to analyze causes of the charge structure in the updraft and downdraft. In such a framework, particle charge within a region may

FIG. 6. Vertical cross sections of net charge density (nC m^{-3}) and general CG initiation locations in the NW–SE direction for the homogeneous environment and NI charging schemes of (a) G85, (b) S91, (c) SP98 and (d) RR. Cross sections are taken during R1's strongest updraft period at $t = 120$ min and $x = 99$ km in each case. Red (blue) colors indicate positive (negative) charge density and yellow symbols indicate the general y locations of +CG and -CG initiation within ± 15 min of the slice time and within a few grid points orthogonal to the slice. The charge regions slope upward into the page where there is stronger updraft (not shown). See adjacent key to specific symbols and shading.

FIG. 7. Same as in Fig. 6 except for the heterogeneous cases at three separate times: (a1)–(d1) $t = 80$ min, (a2)–(d2) $t = 140$ min, and (a3)–(d3) $t = 205$ min, which represents the times before crossing, just after crossing, and after the reflectivity merger, respectively. In addition, (e1)–(e3) shows simultaneous vertical and meridional wind components and cloud water content (q_c). Also plotted are streamlines and the following regions common to all four NI schemes: (e3) charging rate ($\text{pC m}^{-3} \text{s}^{-1}$) and (f3) charge density (nC m^{-3}).

FIG. 7. (Continued)

change with time due to local NI and inductive charging, ion capture, deposition by lightning, and advection. Where local NI and inductive charging rates are large within the *updraft*, they are seen to dominate the other charging mechanisms and one may make reasonable inferences regarding the recent processes contributing to the total charge structure there. Within the cloud-free portion of a *downdraft*, the model's local NI and inductive charging rates are zero and charge may only change via advection, sedimentation of charged particles, deposition by lightning, or ion capture (atmospheric ions or ions produced by lightning). Advection and sedimentation (falling from above) likely dominate.

Given the above preface, in all cases, the lowest charge region within the *updraft* before crossing the boundary (positive for G85 and S91, negative for SP98 and RR; Figs. 7a1–d1) was mainly attributed to inductive charging of graupel (e.g., Figs. 8a1, b1 for G85). The NI charge separation, however, was primarily responsible in all cases for the main midlevel charge region within the *updraft* before crossing (negative for S91 and G85, positive for SP98 and RR). The lighter ice crystals and snow aggregates that gained opposite charge during

such collisions were carried upward into the anvil to form the upper-level charge region. An example of the inductive and NI charging rates for graupel are shown for the G85 NI scheme in Fig. 8. Although the magnitudes differ, wherever NI collisions charged graupel positively, the inductive process generally charged graupel negatively, and vice versa (e.g., Fig. 8; also see M05).

Although *inductive* charging was primarily responsible for the lowest charge region within the *updraft* before crossing the boundary in some cases (Figs. 8a1, b1), sedimentation of charge on graupel/hail previously acquired via *NI* charging was primarily responsible for the formation of the lower negative charge region within the *downdraft* (between 0.5 and 4 km) after the merger in all four NI cases (Fig. 7f3).⁵ A region of strong negative NI charging of graupel was located above and adjacent to the *downdraft* region (Fig. 7e3, $z \approx 8 \text{ km}$; inner contours have negative charging rates with magnitude exceeding $31 \text{ pC m}^{-3} \text{ s}^{-1}$). Figure 7e3

⁵ The positive dipole is not seen in the common charge region analysis because S91 was missing this feature (Fig. 7b3).

FIG. 8. (a1)–(a3) Total NI charging rate in $\text{pC m}^{-3} \text{s}^{-1}$, and (b1)–(b3) total inductive charging rate in $\text{pC m}^{-3} \text{s}^{-1}$ for the G85 scheme and for the same three times and cross sections as shown in Figs. 7a1–a3. These total/net charging rates are dominated by graupel and represent the charge that graupel acquires. The species (such as snow or ice crystals) colliding with the graupel obtains an opposite charge. The NI charging rate (labeled NICR) and inductive charging rate (labeled ICR) contours are shown starting at $1 \text{ pC m}^{-3} \text{s}^{-1}$ with intervals of $5 \text{ pC m}^{-3} \text{s}^{-1}$ for positive (negative) in red (blue). See key for mixing ratio values (q_g) and corresponding shadings. The isotherms and cloud boundary are the same as in Fig. 7. Examples from the other three NI cases are found in the supplemental material.

shows only those charging regions common to all four NI schemes at that time. This common negative charging region encloses a local maximum in negative charging; two NI cases also have stronger negative charging at a higher location in the updraft (not shown). The region charged graupel negatively for all four NI cases due to the low temperatures (T mostly between -20° and -30°C in Fig. 7e3) and low but not negligible cloud mass ($0.1 < q_c < 0.5 \text{ g kg}^{-1}$ in Fig. 7e3) or rime accretion rates. Large ice crystal concentrations (not shown) and graupel mixing ratios help explain the large charging rate magnitudes there.

Although all cases had graupel carrying significant

negative charge in the downdraft, the S91 storm also exhibited significant positive charge in portions of the downdraft and this can likely be attributed to inductive charging experienced just before graupel exited the cloud (not shown).

d. Lightning activity in relation to kinematics, microphysics, and charge structure

As R1 approached and crossed the boundary, G85 and S91 produced fewer $-CG$ flashes (compared to the homogeneous case) and this suggests that $-CG$ flashes may have been suppressed due to the intensifying updraft and lofting phase (consistent with the MacGor-

FIG. 9. Time series plots of 5-min counts of simulated +CG (black filled bar), -CG (hollow bar), and IC (solid line) lightning flashes within a box following storm R1 for the heterogeneous (left column denoted by subscript “1”) and homogeneous environment (right column denoted by subscript “2”) for (a) the G85 NI scheme, (b) the S91 NI scheme, (c) the SP98 NI scheme, and (d) the RR NI scheme. The thin vertical lines across (a1)–(d1) mark important times in the evolution of the R1 storm in the heterogeneous environment: when R1 first begins crossing the boundary (thin dashed), when R1 is noticeably influenced by the cool side air mass (thin solid), and when storms R1 and S1 reflectivity of 50 dBZ merge (thick dotted).

man et al. 1989 hypothesis). The SP98 and RR schemes, however, appeared to result in only a temporary weak reduction in flashes at $t \approx 125$ – 135 min for RR and $t = 130$ – 150 for SP98 (Fig. 9) at about the time the updraft

volume had reached its maximum ($t \sim 130$ min) after crossing.

Also as the boundary was crossed, a stronger and wider updraft lofted the main mid- and upper-level

FIG. 10. Time-height contour plots of 50 total channel segments per level for (a) negative channel segments and (b) positive channel segments for the heterogeneous environment. Channel segments are horizontally summed each 5-min interval within the box following storm R1 for the four NI schemes (G85, S91, SP98, and RR). In other words, everywhere inside the contour represents 50 or more horizontally summed channel segments composed of all IC and CG flashes at that level for a 5-min time interval. Each flash can have more than one segment per level if there is branching or if one or more branches have a horizontal component. The number of segments is also a function of the grid spacing (constant for all simulations herein). (c), (d) Same as (a), (b), respectively, but for the homogeneous environment. A gray horizontal line marks a common reference altitude ($z = 3.5$ km) for easing comparisons.

charge regions for a sustained period (Figs. 7a1–d1 and 7a2–d2). This simultaneously caused the boundary between the upper charge region and the main midlevel region to relocate higher in the storm where the breakdown electric field is also weaker, which in turn shifted IC initiation to higher altitudes. This simultaneous relative increase in IC flashes aloft above ~ 10 km and reduction below ~ 9 km (not shown) might explain why the total IC rate of R1 remained fairly steady during that period (Fig. 9).

Although a small increase in IC flash rates occurred shortly after crossing the boundary at $t = 150$ min, the total IC lightning rate showed the most significant relative increase in all NI cases after 175 min (Fig. 9) due to enhanced charge separation (collision rate) associated with the merger of storms S1 and R1. The charging rate increased with graupel terminal fall speed and number concentration (as both are a function of increased graupel and hail mixing ratios) and occurred over a larger area owing to greater volume of graupel (also seen in Fig. 3 as larger areas of large reflectivity). Enhanced downward graupel flux to low levels (Fig. 8a3; see Fig. 5b downward-sloping graupel contours) was also asso-

ciated with channel propagation moving to lower levels⁶ (Fig. 10) and enhanced CG activity (Fig. 9).

After the merger, in three of four NI cases, increased numbers of +CG flashes occurred (Fig. 9). This was due to the formation of a positive dipole (positive over negative charge) near 7 km AGL at the cloud boundary in the downdraft region, which allowed downward-propagating positive channels. Also, +CG flashes occurred more frequently after the merger because any positive channels that initiated within the dipole could propagate into a larger volume of negatively charged falling graupel at much lower levels (Fig. 10b). The negative charge near $z = 6$ km associated with the dipole is likely forming on lower density graupel and is therefore able to sediment downstream while the

⁶ Although only the 50 per level contour is shown in Fig. 10, the behavior of progressive positive channel descent was consistent no matter what contour from 1 to 100 (per level) was selected for display. However, contours of much larger channel segment values (i.e., >500 per level) did not display this descending behavior clearly or even at all, since those are dominated by the more numerous IC flashes at midlevels.

strong negative charge at much lower levels between $z = 0.5$ and 4 km is associated with higher density graupel and hail, which sediments closer to the updraft. In both cases, large negative NI charging of graupel at low CWC appears to be important. Because the dipole does not form in one case, this lower negative charge region is probably not an extension of the lower half of the dipole. While negative charge at low levels is not a prerequisite for +CG flashes in the model or (as far as is known) in nature, 3D volumetric renderings (not shown) and 2D cross sections of total charge and channels reveal that downward-moving positive channels that initiated above this low-level negative charge region reached lower altitudes compared to those that initiated outside that region (not shown). This negative charge region does not extend all the way to ground, however, as a positive corona current develops within the lowest 0.5–1.0 km.

In summary, the local dipole on the cloud edge (positive above negative) was favorable for downward-propagating positive leaders while the separate extensive negative charge region at low levels apparently assisted the downward propagation of positive leaders such that they were more likely to reach the ground.

e. Comparisons to observations of 2 June 1995

Before starting to make any comparisons between the simulated and observed CG lightning of 2 June, it is important to remind the reader that no observations of the in-cloud lightning structure or charge distribution were available for comparison with the model results. The NLDN CG flash observations are a limited view of a storm's electrical behavior, and thus caution must be exercised in evaluating the performance of a particular NI scheme based solely upon simulated CG behavior. Nevertheless, we will comment below on where each NI scheme simulation did or did not seem to represent observed behavior.

In the homogeneous and heterogeneous simulations, R1 could be best compared to the “warm side storms” and “boundary-crossing storms” from 2 June 1995, respectively. The simulated homogeneous R1 storm was consistent with many of the observed storms that did not cross the boundary, which were strong initially but then weakened. However, the simulated R1 and L1 storms weakened more quickly than in nature. On 2 June, most of the observed boundary-crossing storms increased their 40-dBZ echo-top, maximum radar reflectivity, and low-level rotation (GW02), after crossing the boundary. This was also consistent with the simulated R1 boundary-crossing storm.

The CG flash behavior of R1 in each NI case was also

compared with that of the observed storms to see which aspects of the observations could be reproduced (summarized in Tables 1–3). The goal here was to compare each scheme to the spectrum of behavior for the observed storms. While the four schemes each seemed to reproduce some of the observed CG lightning behaviors, none of the NI schemes reproduced the variation in dominant CG polarity observed within actual 2 June 1995 storms reported by GW02.

For instance, after merging (which occurred after crossing) all schemes but S91 increased in +CG flashes. This was consistent with the observed Sunnyside and Nazareth, Texas, storm behavior (Fig. 11). Furthermore, the –CG dominated behavior typical of the warm side of the boundary was reproduced in only the G85 and S91 cases (cf. the observed storm in Fig. 12). Other comparisons between the simulated and observed storms can be found in Table 1.

There were also discrepancies between the simulated and observed maximum CG flash rates and total CG flashes. For example, compared to the observed storms on the warm side, the maximum simulated 5-min –CG flash rates and total –CG flashes were generally too small for all cases and +CG rates and totals too large for SP98 and RR (see Table 2). This behavior for SP98 and RR was also true for boundary-crossing storms in that the total +CG flashes were much higher than observed for any storm or pair of merging storms (Table 2). The maximum +CG flash rate and totals for the G85 and S91 were not inconsistent with observed values (Table 2). The maximum simulated 5-min –CG flash rates (and –CG totals) for boundary-crossing storms for all NI schemes were also within range of observed values (Table 2).

In most NI cases, the +CG flashes that initiated beneath a downward-sloping, positive dipole in the precipitating downdraft reached ground outside the largest precipitation region (outside the largest radar reflectivity) consistent with many of the +CG flashes documented in Gilmore (2000). However, only in the RR case did some of the +CG flashes occur directly within the large reflectivity core, as was common in GW02, and these initiated aloft on the northwest side of the storm ($z \approx 7$ km and $t = 140$ min; Fig. 7d2; also see Table 3).

f. Discussion

The lightning behavior and charge structure in the simulated R1 storm was modulated by the storm's kinematic and microphysical state, which in turn depended on the local environmental conditions where the storm evolved. Increased production and sedimen-

FIG. 11. (a) Evolution of the 2–3 Jun 1995 Sunnyside (R2), Dimmitt (L2), and Nazareth (S1) storm echo centroid tracks with respect to the mesoscale boundary (radar thinline), base-scan radar reflectivity echoes at select times along the tracks, positive and negative cloud-to-ground lightning flashes (+CG and -CG) for 2.5 min either side of the displayed reflectivity echo times, and selected severe weather (see the key). The S1 and L2 flash symbols are shown in black type while R2 symbols are shown in gray type. Only the largest hail report for each storm is shown here (see GW02 for all reports). All time markers indicate minutes after 2302 UTC. Other storms in the view area are omitted to improve clarity. (b) Composite time series plot of 5-min counts of detected +CG and -CG for R2, L2, and S1 and 40-dBZ reflectivity echo top for R2 (solid line), L2 (gray line), and S1 (dotted line). Times markers are the same as in (a). Associated severe weather and storm behavior are shown along the top of the timeline. Figures adapted from Gilmore (2000). Radar range rings and TX county lines are also indicated for reference.

tation of graupel and hail were associated with increased +CG flashes in three of four NI schemes (all but S91) during and after a merger between the main storm of interest and another storm. The merger occurred after the boundary was crossed. The majority of the CG flashes occurred within the merging precipitation *downdraft* regions at that time. This was also associated with an increased -CG flash rate in two cases (G85 and S91). Because of the commonality of increased +CG flash rate in three of four schemes, this behavior is the focus of the following discussion section.

This general increase in +CG flash rate within the two merged precipitation regions was related to two important factors regarding charge structure there

(Figs. 7a3–d3). The first important factor was the strengthening of a normal dipole that set up at midlevels along the cloud boundary (roughly $z = 7$ km), which favored downward-propagating positive channels in three of the four NI cases. Most of the RR +CG flashes and nearly all of the SP98 and G85 +CG flashes occurring after the boundary crossing and merger fell into this category (see e.g., in column 3 of Fig. 7). In particular, the +CG flash increase during cell merger for the G85 scheme was exclusively due to the midlevel normal dipole. Less common were the +CG flashes in RR and SP98 associated with an inverted tripole in the updraft and these occurred just after crossing the boundary (see Fig. 7d2). Both the normal dipole and

FIG. 12. (a) Same as in Fig. 11a except for the L1 (McDonald-LM) and R1 (McDonald-RM) warm side supercells where times shown are in minutes after 2325 UTC. (b) Same as in Fig. 11b except that flashes are shown for both storms before splitting and only for the R1 storm after splitting. The 40-dBZ reflectivity echo top is also shown for storm R1 (black line) and L1 (gray line). Figures adapted from Gilmore (2000).

inverted tripole are associated with +CG flashes in the model and in nature (e.g., Mansell et al. 2002; Wiens et al. 2005). The second important factor was the negatively charged graupel that descended within the down-

draft region for all four NI cases, and brought negative charge close to ground. While not a requirement for +CG flashes, this descending graupel likely enhanced the probability that the positive channels would reach

TABLE 1. The CG flash characteristics present in the simulated and observed storms. Characteristics are flagged with “✓” for the simulated storms and presented as a fraction for the observed storms (number affected/total qualifying).

Lightning characteristics	NI charging scheme				Fraction of affected obs storms (GW02)
	G85	S91	RR	SP98	
Dramatic +CG increase within 60 min after crossing ^a			✓	✓	5/11
+CG increase during crossing			✓		1/11
Majority of +CG flashes within region > 50 dBZ ^b			✓		7/11
+CG increase after a storm merger	✓		✓	✓	1/1 (pair)
Produced some negative flashes before crossing the boundary	✓	✓			7/9 ^c
-CG dominant for storms not crossing boundary (or homogeneous run)	✓	✓			3/4

^a Often associated with the first appearance of >60 dBZ (in the observed base radar scan).

^b Only occurred for a brief time for RR during crossing. See Table 3 for more information.

^c Only 9 of 11 boundary-crossing storms produced any flashes prior to crossing.

TABLE 2. Relationships between storm location, general lightning class, and maximum +CG and –CG flash rates for 18 of 20 analyzed storms (from GW02) along with the four NI simulations (in boldface type). The CG flash rates were so small in the Progress and Muleshoe, Texas, storms that they were not classified. The general lightning classes N, P, and S represent storms dominated by negative CG lightning, a large increase in positive CG lightning, and storms that switched from positive to negative dominated (see Gilmore and Wicker 2002). There were no cool side storm simulations performed but the cool side storm observations are listed anyway. R1—The original right moving storm. R1/S1—Includes flashes for S1 after it enters the R1 analysis box. Sunnyside/Nazareth—Includes flashes for Nazareth after 0130 UTC when it starts merging with Sunnyside.

Storm name or NI scheme	General lightning class	Max 5 min flash rate of		Tot	
		−CG	+CG	−CG	+CG
Cool side storms					
Joel	N	6	0	9	0
Matador	N	8	2	36	6
Ford	N	7	2	24	12
Nazareth (before 0130 UTC: before merger)	P	1	8	5	31
Landergin	S	9	2	30	8
Muleshoe	n/a	3	1	5	2
Dimmitt	P	3	3	6	9
Friona	P	10	33	56	144
Hereford	P	3	14	16	56
N of Glenrio	P	0	14	0	30
Nara Visa	P	5	14	25	58
Sunnyside /Nazareth (after 0130 UTC: inclusive of merger)	P	2	21	7	68
Glenrio	S	3	2	6	8
Grady	S	7	5	23	19
Olton-Hart-Tulia	S	12	4	133	32
R1/S1: G85	P	5	3	17	15
R1/S1: S91	N	7	2	51	4
R1/S1: SP98	P	0	40	0	492
R1/S1: RR	P	2	17	0	180
Warm side storms					
Denver City	N	14	1	100	1
McDonald RM	N	8	1	15	2
McDonald LM	N	6	1	66	5
Bula	S	3	2	12	6
R1: G85	N	3	1	24	1
R1: S91	N	3	0	32	0
R1: SP98	P	0	7	0	76
R1: RR	P	0	3	0	26

ground.⁷ The 3D renderings and 2D cross sections were used to associate this negative charge region with positive channels (not shown). This negative charge that fell to low levels on graupel/hail was produced in the midlevel updraft ($z = 7\text{--}9$ km) where strong NI charging was occurring in all four NI schemes. In addition, for the RR case, a lowest negative charge region also appeared on hail as the boundary was crossed and +CG flashes occurred coincident in space/time (as previously mentioned in section 4e).

One additional consequence of having negative charge within the low-level downdraft in all four NI cases is that it would make downward-propagating

negative channels less likely there. Although negative CG flashes initiated on the updraft's northwest side in the G85 and S91 cases (Figs. 7a1,a3,b3), they came to ground on the edge of and not within the low-level

TABLE 3. Relationship between CG lightning flash polarity and the 49-dBZ simulated radar reflectivity contour ($z = 1.46$ km) for the four NI charging scheme cases after the storm crossed the boundary.

NI charging scheme	Percentage of flashes inside the 49-dBZ reflectivity contour that were:	
	+CG	–CG
G85	6%	67%
SP98	5%	0%*
S91	0%	68%
RR	5% (61% while crossing)	1%

* Note that SP98 produced no negative CGs anywhere.

⁷ Perhaps this behavior is a more dramatic version of the end-of-storm +CG flashes (e.g., Fuquay 1982) shown in the multicell storm G85 NI case and S91 NI case of M05.

negative charge region. Perhaps this partially explains the weaker increases in $-CG$ flash rates for the G85 and S91 cases after they crossed the boundary compared to the larger $+CG$ increases associated with the RR and SP98 cases.

In light of the model findings, the GW02 hypothesized charge structure model (their Fig. 8b) should be revised to include the current finding of a large volume of negatively charged graupel in the downdraft below the normal dipole. Also, the GW02 “lower positive region” (hypothesized in their Fig. 8b) was found to occur at much higher elevation in the RR and SP98 simulations due to the lofting in the updraft.

In the previous section, the simulations were compared with the GW02 observations in order to determine which scheme was most consistent. None of the schemes performed perfectly (see Tables 1 and 2). The two schemes that were most consistent with reproducing the warm side storm and boundary-crossing storm CG flash observations were G85 and RR. However, even then, G85 (RR) produced too few $-CG$ s (too many $+CG$ s) relative to observations. The scheme that definitely performed worst was S91. If the RR scheme could be improved so that it is able to produce more $-CG$ flashes, then our results suggest that it would probably become the favored scheme for future work as it incorporates more microphysical dependencies than G85. However, many more case studies are needed before general judgments can be made about the NI scheme performance.

Each scheme had various apparent strengths and weaknesses described above; however, as discussed above, inconsistencies do not necessarily result from NI scheme deficiencies alone. For instance, in the microphysics, such improvements that might lessen inconsistencies include explicitly predicting ice particle concentrations, representing a more realistic cloud droplet size distribution, allowing collection efficiencies to vary with particle diameter for each hydrometeor species, allowing collection efficiencies to be altered by the electric field, and predicting an ice particle temperature. For the charging parameterizations, possible improvements include the addition of more parameters known to influence the sign of charge acquired by the rimer during collision such as the relative diffusional growth rates (Baker et al. 1987; Mitzeva et al. 2003), water vapor supersaturation (Saunders et al. 2001, 2003), and the cloud droplet size distribution (e.g., Avila et al. 1999). Improvements to the branched lightning parameterization might include a multiple return stroke capability (although that particular improvement would not be expected to affect the in-cloud charge structure and thus may not change the current results). Further-

more, the environmental conditions of 2 June for both the warm side and boundary-crossing storms might be initialized in a more sophisticated way to include the across-domain variation in CAPE and CIN found on the warm side or the decrease in mixing ratio and CAPE found farther on the cool side (GW02).

5. Conclusions

The numerical experiments herein were kinematically consistent with the observed behavior of nearly all storms that crossed the outflow boundary in west Texas on 2 June 1995; the simulated right-moving supercell storm (R1) showed rapid intensification as it began to interact with the air mass from the other side of the outflow boundary. The 40-dBZ echo-top, updraft speed, and low-level mesocyclone rotation increased in R1 after crossing the boundary. After crossing, R1's increased updraft speed and volume were sustained and caused particles to be lofted higher, which in turn shifted IC flash activity and initiation points to higher altitudes for a period of about 40 min.

Intensification associated with the new environment on the cool side of the boundary also played an important role in the enhancement of graupel and hail volumes, simulated radar reflectivity, cloud water content, and intensification of the inductive charging rates and NI charging rates leading eventually to more frequent CG flashes. The graupel sedimentation and CG flashes also shifted from the southeast to northern side of the storm after crossing the boundary, similar to the observed storms. Later, a precipitation core merger between two supercells on the cool side of the boundary resulted in the production of larger mixing ratios and faster fallout, which in turn increased the charging rates (faster collisions) and lowered and enhanced the middle charge regions. The similarity between the kinematic and microphysical behaviors of the observed and simulated storms suggests that the simplified initialization procedure provided at least some semblance of the storm behavior in the west Texas Panhandle on 2 June 1995.

Despite differences in updraft charge structure, all four NI cases consistently produced a negative charge region at low levels ($z = 0.5\text{--}4$ km), which was dominated by negatively charged graupel that had charged primarily via NI charging and had descended from the midlevel updraft ($z = 7\text{--}9$ km). The presence of a dipole in the downdraft near the cloud boundary (near $z = 7$ km) above this negative charge region in three of the four NI cases favored initiation and downward-propagating positive channels there and was the most common charge structure associated with $+CG$ flashes

at that time. The positive and negative charge densities in this dipole were larger after crossing the boundary as well as after a storm merger, thereby enhancing flash initiation. While not every case showed an actual increase in +CG flashes, we speculate that the negative low-level charge in every NI case and the downward trend of positive channels in every NI case suggests that perhaps all of the schemes were headed in the right direction for simulating increased +CG flash rates observed in the 2 June 1995 boundary-crossing storms.

One of many artificial aspects (and model uncertainty) of the simulations was that most of the NI parameterizations produced a particular polarity of CG flashes but had difficulty or did not produce the opposite polarity. This means that many (three of four) schemes were successful in reproducing behavior from either the warm side or boundary-crossing storms but not both. For example, the S91 regime did reproduce the -CG behavior common to the warm side storms but failed in reproducing the increasingly +CG flash behavior common to boundary crossing storms. The opposite was true for RR and SP98. One exception was G85, which was able to produce both negative CG flashes while on the warm side and increased +CG flashes after crossing: similar to some of the observed boundary-crossing storms. Flash rates and total flashes were also compared to the observed storms. The RR and SP98 cases both produced too many and too frequent +CG flashes relative to the observations for both the warm side and boundary-crossing storms. The S91 and G85 cases produced too few -CG flashes (and rates) in the heterogeneous environment relative to warm side storm observations. Overall, the G85 and RR schemes performed best and S91 performed worst. However, more case study tests of all of these schemes are needed to check consistency of performance. Inconsistencies between the model behavior and the observed storm behavior could also be attributed to the NI charging parameterizations, the simplifying assumptions associated with environmental initialization, and the microphysics and lightning parameterizations.

One of the limitations of the current study was that there were no observed IC lightning rates and no electric field soundings from which to determine charge structure. The 3D lightning mapping, soundings of the charge structure, and perhaps in situ measurements of particle charge (as described, e.g., in MacGorman et al. 2005) should be included in future observational studies of boundary-crossing supercells. Also, our experience with the 2 June 1995 case suggests that future observational field studies should implement frequent soundings over a large area to help characterize the environment. This is because the environment can change rap-

idly with time (Rasmussen et al. 2000) and it is not always clear in advance which environmental locations will give the most favorable prestorm soundings for use in the model.

Future modeling studies initialized with inhomogeneous environments could also address the following additional questions. What are the individual contributions of increased vertical wind shear, CAPE, and water vapor mixing ratio on the microphysics, electrification, and lightning of boundary-crossing supercell storms? If storms experience more gradual changes in the mesoscale environment, rather than the rapid changes associated with a boundary as shown herein, how are the charge structures and lightning affected? Can boundary-crossing storms that remain isolated eventually experience the same sort of charge structure and lightning behavior in the downdraft as those that merge? How are other vivid lightning producers, such as squall lines, affected by environmental changes and/or merging and are processes leading to increased lightning flash rates in those storm types similar to those in boundary-crossing and merging supercells?

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