A Numerical Study of Storm Splitting that Leads to Long-Lived Storms

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ABSTRACT

We have used a three-dimensional cloud model to investigate the splitting of an initially isolated storm in a one-directional east-west shear. The simulated evolution of storm splitting in some cases follows all four stages suggested by Achteimer (1969) after analysis of radar data, including the development of two self-sustaining storms. One of these storms moves to the right of the mean wind vector and the other to the left. In the right-moving storm, the updraft rotates cyclonically and the downdraft anticyclonically, forming a vortex pair, as depicted in the schematic model of Fankhauser (1971). The vortex pair structure is also similar to that observed with Doppler radar and analyzed by Ray (1976). The downdraft-induced gust front interacts with the low-level environmental wind to produce the convergence necessary to sustain the storm. This convergence extends to the south and west of the storm, and if enough low-level moisture is available a flanking line develops. The distribution of rainwater within the updraft suggests the existence of an overhang and hook typically observed in severe storms.

To understand when splitting might occur, the strength and distribution of the vertical wind shear were varied. The various simulations suggest that strong shear at and just above cloud base is important for the splitting process to be successful. For splitting to occur the low-level inflow from the east in our simulations must be sufficiently strong to inhibit the propagation of the gust front toward the east. If the gust front (or wind shift line) can propagate away from the storm toward the east, the region of low-level convergence moves away from the storm and initial splitting in the lower updraft cannot be sustained. Further, without the precipitation-induced downdraft and associated low-level outflow splitting does not occur.

1. Introduction

The various structures of long-lived, self-sustaining supercell storms have been documented through numerous observational case studies (e.g., Browning and Ludlam, 1962; Browning and Donaldson, 1963; Fankhauser, 1971; Marwitz, 1972). These storms typically occur in environmental winds that have strong vertical shear of horizontal winds as the composites of Darkow and McCann (1977) and Fankhauser and Mohr (1977) indicate. The storms interact constructively with this shear in supplying themselves with the moist air needed for their continued existence. The development of these structures, however, has not been studied in detail because observational data are more difficult to obtain and analyze when a storm is undergoing significant changes. Radar data do indicate that one situation in which self-sustaining storms may develop occurs in conjunction with the splitting of a single raincell (e.g., Fujita and Grandoso, 1968; Achteimer, 1969; Charba and Sasaki, 1971; Fankhauser, 1971; Brown et al., 1973; Brown, 1976). Here we investigate this situation with the aid of a three-dimensional storm model developed by Klem and Wilhelmson (1978a). In that paper we reported on a 44 min simulation of a storm embedded in vertically sheared environmental wind that changed direction with height and noted that the initial splitting of the low-level updraft looked as if it might be followed by the development of two self-sustaining storms. We will now investigate the splitting of updrafts during longer integration periods. We will also relate splitting of an initially isolated storm to development of long-lived storms.

One-directional initial wind profiles are used in this investigation to simplify the interactions of the storm with the ambient wind field since a directionally varying environmental wind is not required for splitting to occur. Some observations of splitting storms support this simplification such as those analyzed by Charba and Sasaki (1971) in which strongly sheared winds in the low to mid-troposphere (1–7 km) did not change direction substantially with height when the wind profile is considered relative to pre-split storm motion.
One-directional wind is also advantageous from a computational point of view in our model if the Coriolis force is neglected since the integration domain can be reduced in half due to symmetry across a vertical plane parallel to the wind and cutting through the middle of the initial buoyant region. The use of our current model with a one-directional environmental wind profile and no Coriolis force implies that if a storm splits, each of the split storms will be an exact mirror image of the other through the vertical plane of symmetry.

The investigation of splitting storms in a directionally varying shear field is presented in an associated paper by Klemp and Wilhelmson (1978b; hereafter referred to as III). There it is demonstrated that low-level directional variation of the wind shear plays an important role in selectively enhancing either the right- or left-moving storm during and after splitting.

In Section 2 we briefly describe the storm model presented by Klemp and Wilhelmson (1978a; hereafter referred to as I) and how it is initialized. In Section 3, a description is given of the splitting of an initial storm that leads to the development of two self-sustaining storms. In Section 4 the impact of the strength and vertical distribution of shear on storm splitting will be investigated. We will also discuss several other simulations that are helpful in understanding splitting in Section 5. Section 6 focuses on how the vertical vorticity in the modeled storms relates to observations and how it is produced. Finally, a summary and some conclusions are given in Section 7.

2. Model initialization

All the storms simulated in this paper were made using the model developed by Klemp and Wilhelmson and discussed in detail in I. This model is compressible and is efficiently integrated by separating out sound wave terms and treating them with a smaller time step than that used for the convective processes in order to maintain computational stability. In the simulations reported here the large or convective time step was 15 s, while the small time step was 3 s. The turbulence representation in the model is based on the solution of a turbulence energy equation which includes the influence of local shear, buoyancy and dissipation. Microphysics is parameterized using cloud water and precipitation water as suggested by Kessler (1969). The model was integrated over a 36 km x 36 km x 10 km domain for which \( \Delta x = \Delta y = 1.5 \) km and \( \Delta z = 0.5 \) km. Open lateral boundary conditions allow disturbances to pass out of the domain with little apparent reflection. The Coriolis force is taken to be zero; its inclusion does not significantly affect the splitting process as documented in III.

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*The ordering of our papers, this one being referred to as II, follows the development of our research efforts and not the order of publication.*
moisture fields. The vertical velocity and horizontal wind in the north–south direction were initially zero while the east–west wind profiles used for simulations described in this paper are given in Fig. 2. These profiles differ in structure primarily below 4 km, and have been adjusted so that in each case the active convection remains near the center of the domain in the east–west direction during the integration period. When comparing model results against observations the horizontal model wind vectors can be thought of as almost relative to the storm, with the main variation due to north and south storm movement during the splitting process.

In the simulations the symmetric properties of the solution were used to reduce the computational domain size. Thus, only figures from the southern half of the domain are shown. Mirror image symmetry across the \( y = 0 \) vertical plane (called the plane of symmetry and oriented parallel to the environmental wind and through the center of the initial impulse) can be used to construct the northern half of the domain. The current model can be run in half-domain symmetric mode or full-domain nonsymmetric mode by changing a single input parameter. To simulate 90 min of real time using the plane symmetric domain requires 21 min of CDC 7600 computer time with the grid and time step specifications in this section.

### 3. Simulation of a splitting storm

The splitting storm discussed in this section developed in an initial east–west wind that increased linearly from \(-8\) to \(12\) m s\(^{-1}\) between 0 and 4 km (except for some smoothing of the profile near 4 km) as depicted in Fig. 2a by the curve labeled R20 (indicating a 20 m s\(^{-1}\) total wind variation). The splitting of the developing storm in this simulation can be characterized by the four stages suggested by Achtenmeier (1969) from radar analysis. These stages will be illustrated using horizontal rainwater fields at \( z = 1.75 \) km.

The first or formation stage occurred when precipitation developed in the initial storm. This is illustrated at 30 and 45 min in Figs. 3a and 3b where only the southern half of the storm is shown. The northern half, as mentioned in the last section, is a mirror image of the southern half through the vertical plane at \( y = 0 \). The rainwater field had spread out to the east by 45 min due to precipitation from above. Weaker rainwater gradients occurred in the eastern part of the storm as Achtenmeier observed. In the second or elongation stage the rainwater field extended further to the south (and north), perpendicular to the mean environmental wind vector (Fig. 3c). This stage is followed by the splitting stage in which the central portion of the initial rainwater field rapidly diminished in magnitude as two storms became evident. This is apparent at 75 min in Fig. 3d where the maximum in rainwater no longer occurs at \( y = 0 \). The fourth or deviate stage occurred as the split storms continued to move apart from one another. In R20 the storms moved laterally apart at about 5 m s\(^{-1}\) from 65 to 95 min when the simulation was terminated. Absence of a significant east–west component of motion results from our specification of the initial environmental wind. The initial wind can be changed by the addition of a constant vector when thinking.

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**Fig. 3.** Horizontal cross sections (R20) of rainwater at 1.75 km for 30, 45, 60 and 75 min. The contour interval is 1 g kg\(^{-1}\). In (d) the black dot is the location of maximum vertical vorticity in the cross section and the thin line is the location of the vertical cross sections shown in other figures.
about model and observed storm movement, the latter typically having an east–west component of motion. This adjustment does not alter the physical solution since free-slip boundary conditions for the horizontal velocities are used at the bottom and top of the domain.

A quick overview of the storm development in terms of the maximum updraft and downdraft is given in Fig. 4 by the solid lines. An initial maximum velocity of 12 m s$^{-1}$ occurred at 30 min along the plane of symmetry. By this time some rain had reached the ground and a downdraft had begun to form. As the downdraft formed the updraft subsided somewhat from its initial peak value. It then increased again in the elongation stage that occurred around 60 min. This growth was followed by the splitting stage. The splitting storms had a self-sustaining structure as suggested by the quasi-steady updraft and downdraft maxima after 70 min. In order to study this development in some detail horizontal planes depicting storm evolution at several heights will be presented. Unless otherwise stated, the discussion will be directed toward the development and structure of the southern storm.

Fig. 5 shows the evolution of the velocities at 1.75 km, the same level as the rainwater fields in Fig. 3. The horizontal winds are in vector form and the vertical velocity is contoured. The contour interval is 2 m s$^{-1}$ and the dashed lines are contours in downdraft regions. The rainwater field is enclosed by the thick solid line. The southern half of the updraft was rotating cyclonically at 30 min and the northern half (not shown) anticyclonically (see Section 7 for further discussion). By 45 min the initial updraft had split, with the southern updraft retaining its cyclonic rotation and the northern one its anticyclonic rotation. Concurrent with this splitting was the development of a low-level downdraft separating the updrafts. This development is similar to a shorter shear simulation by Klemp and Wilhelmson (1978a). It is also similar to Schlesinger's (1978) shear simulations. However, from his time history of maximum updraft velocities it appears that his splitting storms were decaying while in the R20 simulation they were not (see Fig. 4). By 75 min the downdraft was also splitting in response to the continued separation and persistence of the split updrafts.

The split of the updraft and subsequently the downdraft at 1.75 km is related directly to the evolution of the flow field beneath the storm at 0.25 km. This is shown in Fig. 6 where the contour interval for the vertical velocity has been changed to 0.5 m s$^{-1}$. The storm was supplied with moist low-level air primarily from the east. By 45 min the main updraft or convergence region had moved toward the south in response to diverging downdraft air. As the convergence

![Graph showing maximum updrafts and downdrafts for R10 (dashed) and R20 (solid) simulations. The short dashed line is a secondary maximum updraft for R10 occurring in an updraft downwind of the rain region.]

![Graph showing horizontal cross sections (R20) at 30, 45, 60 and 75 min showing the horizontal vector winds and the vertical velocity at 1.75 km. Solid contours are used in updrafts and dashed contours in downdrafts. The contour interval is 2 m s$^{-1}$. The maximum horizontal wind speed (m s$^{-1}$) is indicated for each time in parentheses. The thick line is the outline of the rainwater region.]

$^3$ The magnitude of the convergence can be estimated from the vertical velocities at 0.25 km through the anelastic mass con-
below cloud base. This evaporation increased the low-level humidity from about 75 to 90%. At cloud base the downdraft temperature was slightly cooler than that of the initial environmental temperature. The temperature and humidity in the inflow region remained close to that of the initial environmental air. The temperature structure in the east–west vertical cross section that passes through the thin line at \( y = -7.5 \) km in Fig. 7a is shown in Fig. 7b. The depth of the cold outflow is about 500 m as commonly observed (e.g., Goff, 1970). Plotting the maximum potential temperature deviation at each level suggests (not just for \( y = -7.5 \) km) due to quasi-steady storm structure that parcel ascent closely follows a moist adiabat below the maximum updraft level (3.25 km at 75 min) as indicated by the thick line on the skew-\( T \) diagram in Fig. 1.

Pressure distributions are also indicated in Fig. 7. At 0.25 km the high pressure center was associated with the diverging air and the low center with the inflow just to the east of the main updraft. In the vertical cross section the vertical gradient of pressure opposed cloud growth above 1 km.

increased, the elongated updraft changed from an east–west orientation to a north–south one. Coupled with this change is the spread of the outflow towards the south and west. The associated wind shift line or gust front is quite evident in the updraft region at 60 and 75 min. Moist air approaching the storm from the east rises up over the southerly outflow along the gust front and can sustain the updraft provided that the gust front does not move too rapidly away from the storm toward the east. This will be discussed further in the next section.

The thermodynamic structure associated with the low-level outflow at 75 min is shown in Fig. 7a. Air in the outflow region is 3–4°C colder than the initial temperature primarily due to evaporation of rain.

\[ 4 \times 10^{-4} \text{ s}^{-1} \]

\[ 8 \times 10^{-4} \text{ s}^{-1} \]

\[ 2 \text{ m s}^{-1} \]

\[ 1^\circ \text{C} \]

\[ 0.4 \text{ mb} \]

\[ \text{H} \]

\[ \text{L} \]

\[ \text{H} \]

\[ \text{L} \]
The velocity structure at 2.75 km is given in Fig. 8.  Splitting is again evident as the updraft continued to move away from the plane of symmetry in time. The maximum velocity decreased after its initial peak at 30 min and then increased to about 13 m s⁻¹ as low-level convergence increased. The major part of the rain-induced downdraft was located below this level. The downdraft was primarily supplied with environmental air that had passed around the east side of the storm as seen both in this figure and in Fig. 5.

The rainwater field in the eastern part of the updraft region at 75 min overhangs that at lower levels (Figs. 8d and 5d). This can be seen more clearly in Fig. 9 which shows contours of rainwater $q_r$ and cloud water $q_c$ in the $y = -7.5$ km east-west vertical cross section. Below the overhang cloud water exists indicating that air that approached the storm from the east was rising and condensing in this region. Fig. 9 helps to illustrate the self-sustaining structure of the split storms in which rain does not block the inflow of moist low-level air into the updraft, a common occurrence in two-dimensional modeled clouds in shear.

The velocity structure at 4.75 km is shown in Fig. 10. Updraft air was diverging at this level during the simulation since the updraft maximum occurred at or below it. At this and 2.75 km some of the air that approached the storm from the west was accelerating as it was diverted around the storm. High pressure centers associated in part with this blocking flow are indicated by H in the figures. When highs and lows are present in the same figure they differ by roughly 1 mb at 60 and 75 min.

4. The effect of shear intensity and distribution on the splitting process

Observations suggest that splitting storms are often embedded in strong shear, as previously mentioned. In this section we will discuss simulations in which the low-level shear was varied in order to document shear effects on cloud development and splitting. We expect that if the shear approaches zero an initial cloud will grow taller, rain harder and then decay as commonly observed in axisymmetric cloud models. Conversely, if the shear strength becomes excessive significant cloud development will not occur.

We have investigated the effect of shear strength on storm development using the profiles R10, R20, R30 and R21 given in Fig. 2a. The profiles in this figure indicate easterly flow relative to the cloud below ~2 km and westerly flow above. The clouds remain within the domain during an ~90 min integration time, with any substantial movement occurring only in the north–south direction. The R20 simulation with a 20 m s⁻¹ change in velocity over the lower 4 km has
already been presented in the previous section. The R10 simulation with a 10 m s$^{-1}$ change is of particular interest since the low-level updraft was split by the downdraft, but self-sustaining storms did not develop and the storm eventually decayed.

The R10 storm grew in strength to 30 min, when the vertical velocity reached a maximum of 19 m s$^{-1}$, about 7 m s$^{-1}$ stronger than in R20 (see Fig. 4). The downdraft developed rapidly after this time and reached $-8$ m s$^{-1}$ by 40 min, again stronger than in R20. By 45 min the structure had evolved to that shown in Fig. 11 for horizontal planes at 0.25, 1.75, 2.75 and 4.75 km. These levels correspond to Figs. 5b, 6b, 8b and 10b for R20. In the lower levels the downdraft formed along the plane of symmetry ($y=0$) and displaced the updraft laterally. This behavior is similar to the earlier stages of splitting exhibited in the R20 simulation. In fact, the convergent region at 0.25 km in R10 was even stronger than in R20 (Figs. 11a and 6a) due to the stronger downdraft in R10 and the associated increase in gust front wind, i.e., in R10 the maximum outflow velocity toward the south was 20 m s$^{-1}$ while in R20 it was 12 m s$^{-1}$. However, at 1.75 km the split updraft is weaker in R10 and at 2.75 km the maximum updraft still occurred along the plane of symmetry.

In the R10 simulation the stronger low-level convergence was unable to support continued cloud development. This inability is related to the dramatic differences in gust front propagation between R10 and R20 as seen in comparing Figs. 6 and 12. In the R10 simulation, the gust front was moving rapidly outward from the storm in all directions at 60 and 75 min. As a result low-level condensation associated with convergence induced by the gust front was also displaced away from the primary convective region. In particular, new cloud growth occurred primarily to the east of the original downdraft. This new growth was responsible for the secondary updraft maximum (short-dashed line) in Fig. 4 that occurred to the east of the downdraft and in the plane of symmetry. However,
this secondary updraft became separated from the low-level convergence due to rapid eastward gust front propagation and began to decay. Thus, the low-level convergence was insufficient for supporting further development of the southern or eastern updraft in R10.

In the R20 simulation the gust front propagated primarily to the south and west of the storm. Eastward propagation of the front relative to the storm was inhibited by the stronger low-level inflow and thus the low-level convergence continued to support the updraft at middle levels in the cloud. In addition, the gradual movement of this convergent region coincided with the southward propagation of the storm.

Another simulation, R30, was made to determine the effect of stronger shear on splitting. In this case a 30 m s\(^{-1}\) linear increase in wind speed over the lowest 4 km was used as depicted in Fig. 2a. The maximum updraft in this simulation reached a peak of only 6 m s\(^{-1}\) at 30 min. The gust front associated with the downdraft was correspondingly weak and moved very slowly away from the plane of symmetry. The initial cloud did not split; rather it tilted heavily downshear in time and eventually dissipated.

The last simulation in this sequence, R21, was made to determine whether extending the shear above 4 km would affect the splitting process, since shear throughout the cloud layer is often observed. Here the shear from the R20 case was extended up to 8 km as illustrated in Fig. 2a. Although this extension slightly reduced the maximum updraft velocity at 30 min from 12 to 10 m s\(^{-1}\), the simulated storm still split. At 75 min its structure was similar to the R20 storm with a maximum updraft of 11.2 m s\(^{-1}\), 1 m s\(^{-1}\) less than R20. This comparison indicates that shear near and above the level of maximum vertical velocity appears to have less influence on developing storm structure than shear at lower levels. In addition the increased westerly winds at mid and upper levels in R21 did not appreciably alter the propagation speed and direction of the storm.

We have also varied the initial distribution of shear in the lower 4 km. This variation was motivated by some of the observed wind profiles associated with splitting storms that indicate very strong shear in only part of the lower 4–6 km. For example, Brown (1976) and Brown et al. (1973) indicate a concentration of shear at and just above the cloud base. In simulations S1, S2 and S3 a 14 m s\(^{-1}\) vertical variation of the horizontal wind speed across 2 km was centered at the 1, 2 and 3 km levels, respectively (see Fig. 2b). The magnitude of the shear in these profiles is similar to values that have been observed.

At 30 min the storms in these simulations reached their maximum initial updraft intensities of 14, 15 and 17 m s\(^{-1}\), respectively. By 45 min splitting of the lower updraft was evident in all three cases. In the S1 simulation the initial cloud split into two long-lived, self-sustaining, updraft-downdraft structures similar to those in R20.

The initial cloud in the S3 simulation did not split in mid and upper levels and decayed in similar fashion to the R10 simulation. A strong convergent region did develop to the south of the rain area and then grew weaker as the whole convergent region spread out radially from the rain center after 45 min. The propagation of the gust front toward the east, as in the R10 simulation, again appears to be associated with the relatively weaker low-level flow of environmental air from the east. This can be seen for S1 and S3 in Fig. 2b where the mean wind in each profile has been adjusted to maintain the storm in the central portion of the domain.

In the S2 simulation the initial cloud also split, but by 80 min the post-split storms were decaying. This development represents a situation in between that simulated in S1 and in S3. It indicates that splitting can occur and not lead to long-lived storms. Again the reason for storm decay is the propagation of the gust front toward the east, relative to the storms. Simulations S1, S2 and S3 show that as the elevation of the shear layer is increased the storms as a whole propagate more nearly at the low-level wind speed. Consequently, relative low-level inflow is diminished and the gust front can more readily move toward the east and away from the storm.

5. Several other simulations

From the results of the previous simulations it is apparent that if the convergent region induced by the gust front moves toward the east and southeast of the
storm too rapidly, the splitting process cannot be sustained. To further test the sensitivity of the splitting process we increased the initial humidity in the R20 run at 0.25 km from 75 to 85% and at 0.75 km from 85 to 90%. This change was intended to increase updraft and downdraft strengths and thus increase the strength of the gust front relative to the low level inflow.

An updraft of 24 m s\(^{-1}\) and a downdraft of \(-6\) m s\(^{-1}\) developed which are considerably stronger than in the R20 simulation. The maximum southward component in the gust front at 45 min was 23 m s\(^{-1}\), twice that of R20 and even greater than R10. Thus the gust front spread toward the south faster than in R20 as seen in Fig. 13. However, this storm did split in similar fashion to R20 because the gust front did not move to the east relative to the storm. Fig. 13 also indicates a flanking line convergence structure. As observed (e.g., Lemon, 1976b) the moist convection above this convergence region gets stronger and taller as one looks at the flanking line from west to east. Distinct updrafts in the flanking line do not occur apparently due to the limited grid resolution.

Another simulation was made to determine the effect of precipitation on storm splitting. In this simulation the initial conditions were the same as those used in R20, but during the simulation condensed cloud water was not converted into precipitation. The initial cloud did not split and eventually developed a quasi-steady-state structure after 70 min in spite of the absence of a low-level downdraft and the presence of an 0.005 s\(^{-1}\) environmental wind shear below 4 km. Sufficient moisture was available through the lateral boundaries to sustain the storm. The southern half of the updraft rotated cyclonically and the northern half anticyclonically in similar fashion to the initial updraft in previous cases. This result confirms the importance of precipitation-induced downdrafts on the splitting process. It is in contrast to that obtained by Raymond (1976) using a wave-CISK model with which he was able to split a single storm into right- and left-moving ones without including rain processes. Further, a two-dimensional shear was necessary for storm splitting to occur with his model.

Since precipitation-induced downdrafts are important for splitting, another simulation was made to determine the effect of eliminating the evaporation of precipitation (not cloud water) on splitting. Although splitting did occur, the updraft and downdraft were weaker than in the corresponding simulation with rain evaporation (R20) and the updraft remained elongated in the east–west direction. The weaker downdraft was associated with a decrease in magnitude of negative buoyancy, particularly below cloud base where about 1 g kg\(^{-1}\) of water evaporated in the R20 simulation. The lack of evaporation was reflected by the temperature in the downdraft near the ground, which was

Fig. 13. The horizontal cross section of the flow field at 0.25 km and 60 min for the simulation with increased low-level moisture. The vertical velocity contour interval is 0.5 m s\(^{-1}\).

Fig. 14. Horizontal cross sections of vertical vorticity at 1.75 km for R20. The contour interval is 2\(\times\)10\(^{-3}\) s\(^{-1}\). Solid lines indicate positive values and dashed lines negative values. In the light shaded area \(\omega < -1\) m s\(^{-1}\) and in the dark area \(\omega > 1\) m s\(^{-1}\). Maximum updraft and downdraft locations are indicated by plus and minus signs, respectively.
slightly warmer than the initial environmental temperature. In the R20 simulation with evaporation it was about 4°C cooler. The east-west updraft orientation was related to the relatively weak outflow toward the south (or north) and the absence of a strong wind shift line. The weaker downdraft and low-level outflow also led to the slow movement of the storm to the west when compared with the R20 storms.

6. Storm rotation

Rotation of updrafts and downdrafts is frequently observed in severe storms. In this section the evolution and structure of the vertical vorticity in the R20 simulation will be discussed and compared to observations. An initial vortex pair developed in the updraft and was characterized as z = 1.75 km by cyclonic motion (positive vorticity) in the southern half of the updraft as illustrated in Fig. 14a and anticyclonic motion (negative vorticity) in the northern half that is not shown. This vortex pair existed through most of the updraft and increased in magnitude with height from $3 \times 10^{-3}$ s$^{-1}$ near the surface to about $7 \times 10^{-2}$ s$^{-1}$ at 3 km before decreasing.

As the downdraft formed at 1.75 km a new vortex pair was generated having anticyclonic rotation in the southern half and cyclonic rotation in the northern half (Figs. 14b, 14c and 14d). As the downdraft split to follow the right- and left-moving updrafts this vortex pair also separated. It then became more appropriate to consider the rotation in each storm to constitute a vortex pair. This is apparent at 75 min in Figs. 15a–15c which show that the southern storm cyclonic rotation was closely associated with the updraft and anticyclonic rotation with the downdraft. In Figs. 14 and 15 the updraft and downdraft regions greater than 1 m s$^{-1}$ in magnitude are indicated by dark and light shaded regions in which the plus and minus signs indicate their centers, respectively. Fankhauser (1971) indicated a similar structure in his schematic model of two isolated and persistent right-moving Great Plains thunderstorms. Further, there is some evidence of a hook structure in the updraft region in Fig. 3d as observed frequently in severe storm situations. This may result from the rotation of rain near the maximum positive vorticity indicated in that figure by a black dot.

Detailed comparison of this rotation with observations has recently become possible through the use of dual- and triple-Doppler radar systems from which winds and vorticity can be determined. For example, Ray (1976) has calculated the vorticity for storms observed on 20 April and 8 June, during the 1974 NSSL spring program in Oklahoma. On 8 June in the Harrah storm a vortex pair was observed to extend from the ground up to about 8 km. A tornado was embedded in the cyclonically rotating air, but not resolved in the analyses (see Ray et al., 1977). At low to midlevels the positive vorticity occurred primarily in the updraft region and the negative vorticity in the downdraft region (Ray, personal communication). This is similar to the pattern in the R20 simulation discussed in the last paragraph. The maximum positive vorticity determined by Ray (1976) was about 0.015 s$^{-1}$ and the negative vorticity about 0.012 s$^{-1}$, while the corresponding values for the southern R20 storm at 75 min were both about 0.008 s$^{-1}$ (see Figs. 15a–15c where the contour interval is 0.002 s$^{-1}$). The somewhat larger observed values are probably related to the greater intensity of the observed storm and have been further documented for the Harrah storm by Brandes (1977). We note that the horizontal spacing used by Ray is the same as that used in our simulation.

Mechanisms for concentrating vorticity are of particular importance in understanding tornado formation. Thus, estimates of the contribution to vorticity production due to tilting of vortex tubes, convergence (vortex stretching), advection and mixing are of major concern. Several efforts based on observations have been made to determine the contribution of tilting and convergence to the vorticity. Barnes (1968) estimated from rawinsonde and radar data that the contribution of tilting was frequently as great as that expected from convergence in the subcloud layer in a study of 14 storms. In a later study with better updraft estimates for one storm, Barnes (1970) argues that tilting had an effect one order of magnitude greater than convergence on vorticity generation in the lower part of the updraft. Ray (1976) using Doppler data found that for the Harrah storm the tilting and convergence terms were both important. Convergence appeared to be more important at low cloud levels and tilting at least as important as convergence at mid levels.

During the R20 simulation the contribution of convergence, tilting and mixing to the vorticity were computed at several levels. These contributions are represented by the three terms on the right of the vertical vorticity equation

$$\frac{\partial \eta}{\partial t} = -\eta \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + \frac{\partial D_x}{\partial x},$$

where $\eta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$ and $D_x$ and $D_u$ are the subgrid terms for the $v$ and $u$ momentum equations defined in I. The contribution of diffusion is notably less than that due to tilting or convergence in the strong vorticity regions at all times. The vortex pair in the initial updraft resulted from tilting, with convergence becoming more important as vorticity increased.

The production of vorticity by convergence and tilting is shown at 75 min in Figs. 15d–15i for the southern storm at the same levels as the vorticity in Figs. 15a–15c, but with a contour interval of $10^{-3}$ s$^{-2}$. The production rates are similar for the quasi-steady circula-
Fig. 15. Horizontal cross sections of vertical vorticity and vorticity production due to convergence and tilting for R20 at 75 min and 0.75, 1.75 and 2.75 km. The vorticity is shown in (a), (b) and (c) with a contour interval of $2 \times 10^{-5}$ s$^{-1}$, production by convergence is contoured in (d), (e) and (f) with a $0.5 \times 10^{-5}$ s$^{-1}$ interval, and production by tilting in (g), (h) and (i) with the same interval. Solid lines indicate positive values and dashed lines negative values. In the light shaded area $w < -1$ m s$^{-1}$ and in the dark area $w > 1$ m s$^{-1}$. Maximum updraft and downdraft locations are indicated by plus and minus signs, respectively.

convergence. However, convergence tends to have the largest positive effect on positive vorticity production near the updraft center while tilting is almost zero in maximum updraft regions since $\partial w/\partial x = \partial w/\partial y = 0$ there. Convergence also counters negative vorticity production by tilting in the updraft. A more detailed study is planned for a simulation of an observed supercell, including the contribution of vorticity advection. The importance of this contribution can be seen with the aid of Fig. 15 after noting that the storm is quasi-steady at this time and thus the sum of the contributions to vorticity change must be close to zero apart from horizontal storm movement. The current analysis indicates that both convergence and tilting are important in the production of vorticity as also indicated by observational studies.

7. Conclusions

In this paper we have shown that it is possible to simulate the splitting of an isolated storm that is embedded in a one-directional shear. This process is initiated by the formation of a precipitation-induced downdraft which splits the low-level updraft. The low-level split updrafts which are located on the right and left flanks of the storm are supplied with moisture within a convergence zone that develops along a
downdraft-induced gust front. The low-level updrafts continue to separate along with the gust front and convergence zone. The upper part of the updrafts as they are fed from below also separate and the downdraft splits to follow the updrafts. The two split storms are organized to sustain themselves with precipitation falling out of the updraft into the downdraft which in turn undercut the updraft along the gust front, similar to that of left- and right-moving supercells. In this regard, the updraft of the right-moving storm rotates cyclonically and the downdraft anticyclonically. Further, the distribution of the rain field suggests the existence of an overhang and hook commonly associated with severe storms.

The splitting process is a continuous one in which two storms form from one in agreement with Charba and Sasaki's (1971) analysis of multiple-splitting storms on 3 April 1964 in Oklahoma. Alternatively, Fujita and Grandoso (1968) proposed that splitting was a discrete process in which new updraft development occurred within counterrotating wake vortices. Three updrafts then coexist during one stage of splitting. The possibility of new updraft development in wake vortices has also been noted by Jessup (1972) and Lemon (1976a). However, such development has not been observed in any model simulations made.

In order to understand when splitting might occur the strength and distribution of the vertical wind shear were varied. The various simulations suggest that strong shear at and just above cloud base is important for initial low-level splitting to lead to the development of self-sustaining storms. For successful splitting to occur in our simulations using an initial east–west wind profile the low-level inflow from the east must be sufficiently strong to inhibit the rapid propagation of the gust front toward the east. If the gust front (or wind shift line) can propagate away from the storm toward the east, the region of low-level convergence also moves away from the storm and the initial splitting in the lower updraft cannot be sustained. For example, in the limit of no shear an axisymmetric cloud would develop and the gust front would propagate radially outward with equal strength in all directions. The low-level convergence would also move away from the cloud and weaken due to radial expansion. Any clouds that might develop along the gust front would not have sufficient time or moisture supply to maintain a continuously moving deep updraft.

This study indicates that strong low-level shear is necessary for a storm to be able to split into two self-sustaining ones. Because the movement of the gust front relative to the storms is an important factor in splitting, the effects of adding frictional drag on the winds near the ground should be investigated. It is also important in understanding storms splitting to verify current findings for storms that compare in intensity with those commonly observed. Finally, since most splitting storms do not occur in a completely one-directional shear, the impact of two-directional shear on storm development should be studied. An initial study has been reported by Klemp and Wilhelmson (1976b).

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