Simulations of Right- and Left-Moving Storms Produced Through Storm Splitting

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ABSTRACT

Using a three-dimensional numerical cloud model, self-sustaining right- and left-moving storms are simulated which arise through splitting of the original storm. The right-moving storm develops a structure which bears strong resemblance to Browning’s (1964) conceptual model, while the left-moving storm has mirror image characteristics. By altering the direction of the environmental shear at low and middle levels, either the right- or the left-moving storm can be selectively enhanced. Specifically, if the wind hodograph turns clockwise with height, a single right-moving storm evolves from the splitting process. Conversely, counterclockwise turning of the hodograph favors development of the left-moving storm.

1. Introduction

Strong convective storms are frequently observed to propagate consistently to the right of the mean direction of the environmental winds. In many cases such storms actually contain clusters of individual cells and rightward propagation is due to the preferred formation of new cells along the right flank of the convective region (e.g., Newton and Katz, 1958; Newton and Fankhauser, 1975). However, in some situations strong and basically single-celled structures exist which maintain their intensity through continuous propagation to the right of the mean wind (e.g., Browning and Donaldson, 1963; Haglund, 1969; Marwitz and Berry, 1971; Marwitz, 1972). Storms which deviate to the left of the mean wind have also been observed (e.g., Hammond, 1967; Charba and Sasaki, 1971), although with much lower frequency than right-moving ones.

Observational data indicate that for a right-moving storm the flow at low and middle levels relative to the storm approaches from the front and right flanks, respectively, while the opposite is true for a left-moving storm (e.g., Browning and Ludlam, 1962; Hammond, 1967; Darkow and McCann, 1977). Browning (1968) and Fankhauser (1971) described how this orientation of low and middle level winds relative to a storm can be met either by a storm moving to the right of and slower than the mean wind or by a storm traveling faster than and to the left of the wind. However, this analysis does not distinguish which storm(s) would actually persist for a given sounding. An objective of this paper is to present qualitative criteria for distinguishing the conditions favorable for preferential development of either the right-moving or left-moving storm.

Wilhelmson and Klemp (1977, hereafter referred to as II) used a three-dimensional cloud model reported by Klemp and Wilhelmson (1978, hereafter referred to as I) to study the mechanisms of storm splitting. Using one-directional wind profiles, we found that the tendency of an initial storm to split into two self-sustaining storms is strongly dependent on the intensity and distribution of the low-level shear. When splitting does occur, a cyclonically rotating updraft propagates to the right of the initial wind, while an anticyclonically rotating one moves to the left. Owing to the one-directional environmental wind and the absence of Coriolis effects, the split storms which arise in these simulations are mirror images of each other. In that study it was also found that splitting can occur when low-level convergence produced by interaction between the downdraft-induced gust front and the low-level environmental wind moves with the storm, rather than out ahead of it.

In the current study we shall begin in Section 2 by further documenting the structures of the right- and left-moving storms which develop in a one-directional environmental wind shear. Here the Coriolis force is included in the model and comparisons will be provided
in order to assess its influence on storm structure. Subsequent to splitting, the right-moving storm produced by the numerical model displays strong similarities with Browning's (1964) three-dimensional conceptual model for a single-cell right-moving storm. An important feature of this structure is the downdraft located along the left flank supplied by middle-level air which approaches the storm from its right flank and passes around the front side of the updraft. More recent observations have largely substantiated Browning's model as one possible structure for right-moving storms (e.g., Haglund, 1969) and in mirror image for a storm deviating to the left (e.g., Hammond, 1967).

Based on the characteristics of these simulated storms and an understanding of the splitting processes described in II, we propose that an individual right-moving or left-moving storm can arise following the splitting process if environmental conditions favor the selective enhancement of one of the storms. In particular, clockwise turning of the environmental wind hodograph with height would be expected to increase the middle level inflow into the downdraft of the right-moving storm and inhibit flow into the corresponding downdraft of the left mover. This supply of middle level air to the downdraft appears to be necessary for sustaining the storm intensity. Conversely, counter-clockwise turning of the hodograph would have the reverse effect and enhance the left-moving storm. In Sections 3 and 4, individual right- and left-moving storms, respectively, are simulated by including appropriate lower level shear in the direction (north-south) normal to the primary shear (east-west). These simulations reveal that the self-sustaining severe (right- or left-moving) storm originates through a splitting process similar to that occurring in the onedirectional shear simulation, with the second cell subsequently decaying due to the unfavorable nature of the relative middle level winds. Section 5 includes a summary of results and some general comments.

2. Structure of self-sustaining storms produced through splitting

As mentioned above, storm splitting was investigated in II through three-dimensional model simulations in which the environmental shear was initially one-directional. In this section, we further consider the structure of the storms after splitting and compare their characteristics with Browning's (1964) conceptual model. The particular storms to be discussed here are generated by the same environmental conditions as those used in II for the case in which the wind profile contains a 20 m s⁻¹ linear increase in velocity across the lowest 4 km, with a constant wind above this height.

The three-dimensional cloud model is described in detail in I, where the performance of the important features of the model is also evaluated. This model solves the compressible equations of motion using a separate small time step to efficiency handle sound wave processes. The turbulence representation is based on the solution of a turbulence energy equation so that the level of turbulence is influenced by local shear, buoyancy and dissipation. Microphysical processes are incorporated using a Kessler-type parameterization and the ice phase is not presently included. Open lateral boundaries allow disturbances to pass through the boundaries with little apparent reflection.

In the present investigation the Coriolis terms are included in the equations of motion solved by the model. As a result, the initial pressure and potential temperature fields must be slightly adjusted to insure that the pressure is initially in geostrophic balance with the specified environmental wind field. This is accomplished by horizontally integrating the geostrophic wind equations to balance the pressure field and then adjusting the potential temperature such that the hydrostatic equation remains satisfied as described in I.

The temperature and moisture profiles used in the model simulations are depicted in Fig. 1. Convection is initiated by axisymmetric, low-level temperature and moisture perturbations as described in I and II. In the center of the domain the initial perturbations have maximum amplitude and vary with height as shown in Fig. 1. The wind hodograph is depicted in

Fig. 1. Skew T diagram showing initial temperature and moisture profiles in heavy solid lines. Heavy dashed lines indicate the maximum perturbation amplitudes in the center of the domain used to initiate convention. The dot-dashed line denotes the 23°C moist adiabat.
Based on these initial conditions the numerical model is integrated forward in time as outlined in I. The size of the integration domain is 36 km in each horizontal direction, with a mesh interval of 1.5 km and 10 km in the vertical, with a grid spacing of 500 m. During the simulation the initial updraft splits into two cells propagating laterally apart with the right-moving updraft rotating cyclonically and the left-moving one anticyclonically (see II). This splitting is well illustrated by the rainwater contours at 30 min intervals as shown in Fig. 3. Here the x axis is in the direction of the shear vector, with the origin taken relative to $\Theta$ in Fig. 2. We shall examine the storm structure after 90 min of simulation, when the left- and right-moving cells are completely separated.

Since the environmental shear is unidirectional, the split storms would be exact mirror images of each other except for the influence of the Coriolis force. At 90 min the right- and left-moving storms are qualitatively similar, indicating that the Coriolis terms have not yet strongly affected the overall solution. For this reason we shall primarily discuss the right-moving storm with the understanding that the left-moving counterpart is similar in many respects. Certain apparent differences between the two storms will be discussed later in this section and comparisons will be made with a simulation in which Coriolis effects are omitted.

The dynamic structure of the storms can be inferred from the superimposed plots of horizontal wind vectors, vertical velocities and rainwater boundaries in Fig. 4. This figure reveals a structure which is qualitatively very similar to Browning's (1964) proposed model outlined in Fig. 5. [For a one-directional shear profile as in Fig. 5a, Browning (1968) noted that a mirror image left-moving storm would also be expected to form.] The wind vectors in Fig. 4 are relative to the

Fig. 2. Wind hodograph depicting the one-directional environmental wind shear. The thin arrows represent the 0, 2 and 4 km wind vectors relative to an assumed ground based origin at $\Theta$. Heavy arrows labeled SR and SL describe the propagation of the right and left moving storms, respectively.

Fig. 3. Horizontal cross section of rainwater contours at 30 min intervals at $z=2.25$ km. Labeled contours are in units of g kg$^{-1}$. 

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coordinate origin in Fig. 2 and thus are not quite relative to the storm motion since the storms are moving laterally apart at a speed of about 5 m s$^{-1}$. For the right-moving storm moisture is supplied through low-level inflow from the east (Fig. 4a) and is carried upward through a cyclonically rotating updraft (Figs. 4b and 4c). In the upper part of the storm outflow from the updraft is swept downstream to the east producing a pair of merging anvils (Fig. 4d) as occasionally observed in split storms (e.g., Fujita and Gradnose, 1968). Although the undisturbed flow is in the east–west plane, the right-moving storm induces a flow at middle levels which passes around the east side of the updraft from the south and feeds into the downdraft located on the north side of the updraft (Fig. 4b) as suggested by Browning in Fig. 5. In addition, the downdraft observed in Fig. 4b is supplied by flow from the west which develops anticyclonic rotation. The main downdraft is confined almost entirely beneath the level of maximum updraft velocity (Fig. 4c). The downdraft associated with this right-moving storm then spreads out just above the ground to the south and west underneath the updraft (Fig. 4a). The resulting gust front forming along the right flank of the storm produces strong low-level convergence which forces uplifting of the moist inflow from the east to sustain the updraft. This gust front induced convergence appears to govern the storm’s propagation as discussed in II and as also suggested by Moncrieff and Miller (1976) based on the simulation of a tropical storm.

At this time the right moving storm is propagating to the south at about 2.5 m s$^{-1}$, while the left moving storm is moving north at a similar speed in the coordinate framework of the numerical simulation. Based on an assumed origin relative to the ground at $\odot$ in Fig. 2, propagation of the right (SR, using Browning’s notation) and left (SL) moving storms is denoted with the heavy solid arrows.
fortunately, the present model resolution is insufficient to adequately represent this feature which is even less pronounced in the slightly weaker left-moving storm. Nevertheless, the relative orientation of the updraft and rainwater fields are consistent with observed hook echoes (Browning, 1965). The cyclonic rotation within the updraft, apparent in Figs. 4b and 5c, could be sweeping the rainwater around the updraft and into the hook as suggested by Browning (1964).

In Fig. 5c the maximum vertical vorticity of $1.1 \times 10^{-4}$ s$^{-1}$ in the southern updraft is nearly double the magnitude of the negative vorticity in the northern updraft. Thus, although the right-moving storm is only slightly stronger in terms of updraft intensity and production of rain, the Coriolis effects provide a significant relative enhancement of its cyclonic vorticity. This vorticity is similar in magnitude to that observed in hook echo circulations in tornadic storms (e.g., Brown et al., 1971; Fujita, 1973). The negative vorticity in the western portion of the downdraft is considerably stronger than its positive counterpart in the left-moving storm. Although the reasons for this are not entirely clear,

In Figs. 6 and 7 west–east and south–north cross sections are presented which pass through the point of maximum updraft velocity in the right-moving storm (corresponding to the maximum $w$ in Fig. 4c). The vector plots reveal that the southern updraft tilts upstream to the west and north with height while at lower levels the rain is displaced into the downdraft to the north and west of the updraft. Strong vertical velocities in the lower portion of the updraft appear to produce a “weak echo” region between 0 and 2 km above the ground with the rain field overhanging above 3 km to the east and south. The maximum downdraft occurs at $z = 2.25$ km, the maximum updraft at 3.75 km and rainwater extends as high as 7.5 km. The profiles of the perturbation potential temperature (deviations from the initial, undisturbed temperature) in Figs. 6b and 7b reveal that the updrafts develop about 4°C of buoyancy, while the cold downdraft outflow produces up to about 3.5°C of cooling near the ground. The thin layer of negative temperature perturbations just above the ground reflects the shallow cold outflow behind the gust front.

In order to investigate the suggestion of a weak echo region in greater detail, the horizontal contours of rainwater, vertical velocity and vorticity at $z = 2.25$ km are reproduced in Fig. 8. Notice that the rainwater field exhibits an indication of a hook structure in the vicinity of the maximum updraft in the right-moving storm. This “hook” is in the same location as the weak echo region apparent in Figs. 6 and 7 and is directly above the slight indentation also present in the rainwater field just above the ground (Fig. 4a). Un-

![Fig. 5. Browning's model for the structure of a right-moving storm (SR). (a) Hodograph illustrating low (L), middle (M), and upper (H) level wind vectors relative to the ground. The open circle denotes the velocity of the storm. (b) Three-dimensional model of the airflow within an SR storm. Circulations are schematically represented relative to the storm without regard to convergence. Also shown are the approximate extent of precipitation at the surface (hatched area), and positions of the surface gust front and the tornado (when present) (From Browning, 1964).](image-url)

![Fig. 6. West–east cross sections at 90 min taken through the position of maximum updraft velocity in the right moving storm. (a) Vector plot with rainwater contours (g kg$^{-1}$) superimposed (max vector=16.1 m s$^{-1}$) and (b) perturbation potential temperature (°C). Heavy dashed line denotes the rainwater boundary.](image-url)
notice that the flow into the downdraft from the west in Fig. 4b appears much stronger in the right-moving storm than in the left mover.

Further indications of the influence of the Coriolis force are provided in Figs. 8d, 8e and 8f which display the corresponding circulation with the Coriolis terms removed. Here only the southern half of the domain is shown since the rainwater and vertical velocity contours are symmetric about the y=0 axis while the vorticity is antisymmetric. Comparing the two simulations it appears that although the Coriolis force tends to enhance the strength of the right-moving storm, it is apparently not of fundamental importance in sustaining the storm structure.

Although the simulated storms display many similarities with Browning's (1964) model, certain differences are suggested which should be mentioned. Perhaps the most important is that our simulated storm is not nearly as intense as those which are observed to have this structure. This may explain why the right-moving storm does not deviate as far to the right (Fig. 2) as suggested in Fig. 5. In order to maintain adequate numerical resolution in the vertical we have limited the height of the domain to 10 km and have inhibited further vertical growth of the storm by gradually increasing the ambient stability in the upper portion of the domain (see Fig. 1). Thus the simulated levels of maximum vertical velocity, of middle level inflow into the downdraft and of anvil formation are lower than in observations of most strong storms. In addition, the downdraft in the simulation is partially fed by westerly air along the rear flank of the storm which is in contrast to Browning's model. However, this behavior is supported by observations (e.g., Marwitz, 1972).

3. Simulation of a right-moving storm

In the simulated storms with a one-directional environmental wind field, both the right- and left-moving storms appear to have a similar opportunity to persist after splitting. However, by also including shear in the normal direction it should be possible to selectively enhance one of the two storms. In particular, based on Browning's (1964) model and the simulated storms in the previous section, it appears that including a middle level environmental flow from the south would enhance the flow passing around the east side of the updraft and into the downdraft in the right-moving storm and inhibit this flow in the left mover. Without a sufficient supply of environmental air to the downdraft the low-level outflow and corresponding convergence along the gust front is weakened, causing the cell to decay.

To examine this selective enhancement process we altered the shear profile in the previous section to increase the middle level flow from the south. This wind field, shown in Fig. 9, differs from the one-directional shear in Fig. 2 primarily by the addition of north–south shear of 0.001 s⁻¹ across the lowest 2 km and 0.0055 s⁻¹ between 2 and 4 km. In Fig. 9, if the wind at 2 km is such that the hodograph forms a straight line, the environmental wind would correspond to a one-directional shear profile and, if splitting occurred, both right- and left-moving storms would be expected to form. If the middle level (2 km) wind is oriented so the hodograph turns in a clockwise direction with height (as in Fig. 9), relative enhancement of southerly, middle level winds should favor development of the right-moving storm as described above. For clarification, when we speak of the wind hodograph we refer to the curve which passes through the end point of the horizontal wind vector at all heights. Thus by referring to a clockwise turning of the hodograph with height we mean that moving along the hodograph in the direction of increasing height, the curve turns to the right. (We are not referring to turning of the wind vector with height.) This curvature is therefore independent of the location of the origin of the wind vectors.

In order to maintain the storm within the central portion of the integration domain winds are specified relative to the coordinate origin indicated in Fig. 9. This hodograph better resembles observed storm situa-
tions, however, if we assume that the winds relative to the ground are oriented with respect to an assumed origin at $\otimes$ in the figure. Relative to $\otimes$, the wind varies with height from southerly at low levels to northwesterly at upper levels. In the absence of surface effects, cloud development in the model is independent of the location of $\otimes$. For convenience in discussing the model results all descriptions and figures are relative to the coordinate origin in Fig. 9 unless otherwise noted.

Except for the altered wind field the conditions in the simulation described here are the same as those of the previous section. In this case splitting appears to occur in the same manner described in II except that the left-moving storm is weaker on formation and decays with time as the storms move apart. Fig. 10 illustrates the relative strengths of the right- and left-moving storms at 50 min, shortly after splitting has taken place. Notice the strong flow around the east side of the southern updraft and into the downdraft as in Browning’s schematic model. Since the left-moving storm produces a small cloud but no rainwater, this splitting would be observationally difficult to detect.

The locations of the maximum updraft intensity of the left- and right-moving storms are plotted at 10 min intervals in Fig. 11 relative to origin of the coordinates in Fig. 9. The associated maximum updraft velocities indicate that the right-moving storm intensifies after splitting while the northern cell rapidly decays until it completely disappears after about 70 min. Although the right-moving updraft is weakening after 80 min, continuing the simulation to 2 h indicates that the maximum updraft velocity becomes nearly steady at about 11 m s$^{-1}$. The average propagation speed of the right-moving storm between 80 and 100 min is directed toward the south-southwest at about 2.6 m s$^{-1}$ relative to the coordinate framework of the numerical simulation. However, relative to an assumed ground-based origin at $\otimes$ the right-moving storm moves to the right of the environmental wind at all levels as indicated by the heavy solid arrow labeled SR in Fig. 9.

The structure of this persisting storm is qualitatively similar to the right-moving storm described in the previous section. At 90 min its features are exhibited in Fig. 12 through horizontal cross sections at four different levels. The wind vectors are relative to the
Fig. 9. Wind hodograph which produces enhancement of the right-moving storm. Thin solid arrows denote the 0, 2 and 4 km wind vectors relative to an assumed ground based origin at \( \Theta \). The heavy solid arrow labeled SR represents the propagation of the right-moving storm. The heavy dashed arrow characterizes the movement of a left-moving storm which would arise if the 2 km wind vector were altered to the position shown by the thin dashed arrow labeled 2 km.

Fig. 10. Horizontal vector plot at 50 min at \( z = 2.25 \) km with the vertical velocity field superimposed (m s\(^{-1}\)). The maximum vector corresponds to 11.1 m s\(^{-1}\) and the heavy dashed line encloses the rainwater field.

cordinate origin of the hodograph in Fig. 9. Here the orientations of low and upper level winds are rotated clockwise by about 35° relative to the one-directional shear profile in Section 2 owing to the presence of the north–south shear. Thus the low-level inflow is supplied from the southeast (Fig. 12a) while the upper level outflow into the anvil spreads out toward the southeast (Fig. 12d). Since the storm in Fig. 12 is propagating to the west-southwest at just over 2.5 m s\(^{-1}\) as indicated in Fig. 11, this outflow relative to the storm is oriented about 30° to the north of the low-level inflow (see

Fig. 11. Propagation of the location of the maximum updraft for the right- and left-moving storms produced by the hodograph in Fig. 9. Storm positions are labeled at 10 min intervals with the maximum updraft velocities indicated in parentheses. Environmental wind vectors relative to the coordinate origin in the numerical simulation are also included for reference.
Fig. 12. Horizontal cross sections as in Fig. 4 for the right-moving storm produced by the hodograph in Fig. 9: (a) max vector = 14.5 m s\(^{-1}\), (b) max vector = 10.2 m s\(^{-1}\), (c) max vector = 14.9 m s\(^{-1}\), (d) max vector = 18.4 m s\(^{-1}\).

Fig. 9). Because of the decay of the left-moving storm, strong environmental flow passes around both sides of the right moving storm at upper levels (Figs. 12c and 12d). At \(z = 2.25\ km\) strong flow from the south side of the storm passes around the east side of the updraft and into the downdraft on the north side (Fig. 12b). The weak downdraft to the west of the updraft at \(z = 2.25\ km\) (Fig. 12b) is possibly due to blocking westerly flow by the storm forcing the approaching air to descend rather than flow around the storm. Again the cold downdraft spreads out just above the ground, toward the southwest, west and northwest (Fig. 12a). Strong cyclonic vorticity, \(10^{-2}\ m^{-1}\) in magnitude, is generated along the edge of the gust front directly below the center of the updraft and may be related to tornado formation.

The vertical velocity contours in Fig. 12a again emphasize the strong uplifting caused by the convergence line which forms along the gust front. This uplifting continuously provides low-level condensation along the right flank of the storm which is then swept up into the cloud. As in the previous simulation, convergence associated with the gust front seems to provide a dominant influence in steering the storm to the right of the mean winds and allowing the storm to sustain itself. Near cloud base, the cloud extends to the west along the convergence line. This line can probably be identified with the "flanking line" mentioned in various observational studies (Lemon, 1976).

West–east and south–north cross sections oriented through the location of the maximum updraft velocity are included in Figs. 13 and 14. Here an updraft tilt to the north with height is evident, along with the low-level displacement of the rain field to the north and west of the updraft. The lower portion of the updraft is relatively free of rainwater suggesting a weak echo region with rainwater overhanging at middle levels to the southeast. Potential temperature perturbations from the initial state in Fig. 13b reflect an updraft buoyancy and a shallow downdraft outflow.
that are similar to those in the previous one-directional shear case (Fig. 6b). In Fig. 14b the south–north perturbation pressure contours display a negative north to south pressure gradient across the updraft and a slight pressure minimum underneath the updraft. This low-level pressure minimum is in the same location as the meso-low observed in association with severe storms (Charba and Sasaki, 1971). Although these simulated pressure variations are small in amplitude, they might increase to observed magnitudes of several millibars for storms of stronger intensity.

It has been suggested that the deviate motion of the storm relative to the mean wind is caused by a rotational or magnus effect (e.g., Fujita and Grandoso, 1968). In the current simulation, however, this effect does not appear to be significant; as mentioned above, the moist low-level convergence along the right flank is more likely to account for the propagation of the storm. The north–south pressure gradient across the storm at upper levels may arise from a partial blocking due to the earlier presence of the weaker left-moving cell. This blocking would produce a pressure gradient across the storm by simple Bernoulli effects. Blocking is particularly evident in the simulation with one-directional shear in the previous section (Fig. 4d).

At 90 min air flowing around the left flank of the storm at upper levels is generating rather strong anticyclonic vorticity as illustrated in Fig. 15. A weak updraft region forming just north of the main updraft, above the principal downdraft (Fig. 12c), produces

Fig. 15. Horizontal vector plot for central portion of domain at 90 min and at z=3.75 km with vertical vorticity contours (s⁻¹×10⁹) superimposed. Here the heavy dashed line denotes the cloud water boundary instead of rainwater.
condensation which in turn enhances the turbulent mixing (see I). Consequently, this negative vorticity is conceivably produced either through tilting processes or by shear stresses caused by direct entrainment of environmental air (Fig. 15). In any event, by 90 min the upper level environmental air now flows around a vortex pair in which the maximum positive and negative vorticities are comparable (see Fig. 15). In spite of this, the storm continues to deviate to the south. This secondary updraft with anticyclonic rotation does not appear to encourage further splitting. In continuing the simulation to 2 h the storm structure remains about the same with no indications of further splitting tendencies.

For comparison purposes, the simulation described in this section was recomputed using all of the same conditions except that no rain was allowed to form. In this case the resulting storm structure differed significantly from that in the simulation described above. With rain present the downdraft-induced gust front produced strong low-level convergence along the right flank which induced splitting and the subsequent steering of the storm to the right. Without rain, no strong downdraft formed at low levels (because of the absence of rainwater loading) and consequently splitting did not occur. Since the low-level moist inflow was not cut off by a developing downdraft the cloud was able to maintain a nearly steady structure with a maximum updraft velocity of about 15 m s\(^{-1}\). However, in this simulation without rain the storm did not deviate noticeably to the right. Relative to \(\odot\) in Fig. 9, this storm propagated directly east at 3.5 m s\(^{-1}\). These results are in agreement with a similar comparison described in II for a one-directional wind shear and emphasize the influence of rain processes on storm splitting and propagation.

4. Enhancement of the left-moving storm

In order to enhance the formation of the left-moving storm we seek to reverse the relative direction of the middle level winds. This is accomplished here by specifying the wind field according to the hodograph depicted in Fig. 16. For variety, this hodograph is not constructed to be a mirror image of the hodograph in Fig. 9. The origin of the axes in the hodograph was again selected to keep the storm from propagating out of the integration domain. We may assume, however, that the winds relative to the ground are oriented with respect to \(\odot\) in Fig. 16. In this framework, a surface level wind of 10 m s\(^{-1}\) from the south turns to 10 m s\(^{-1}\) from the west at 2 km and then increases to 20 m s\(^{-1}\) from the west at and above 4 km.

As mentioned in the previous section, if the 2 km wind was located such that the hodograph formed a straight line the shear profile would be exactly one-directional and both right- and left-moving storms could persist if splitting occurs. By specifying a hodograph which turns counterclockwise (i.e., to the left) with height as in Fig. 16, an enhanced northerly flow at middle levels should selectively favor development of the left-moving storm.

The simulation of the left-moving storm is conducted in the same manner as in the previous section except for the change in the wind profile to that in Fig. 16. As before, the initial updraft splits, only in this case the northern updraft is considerably stronger. Note the strong anticyclonic circulation from the north which feeds into the downdraft at 50 min in Fig. 17. Following splitting the two storms propagate apart relative to the coordinates of the numerical simulation as shown in Fig. 18. From the maximum updraft intensities it is apparent that although the right-moving cell does not disappear, it remains considerably weaker than the left-moving storm. The average propagation speeds of the two cells between 80 and 100 min are plotted on the hodograph in Fig. 16 relative to the assumed origin at \(\odot\) with heavy solid arrows labeled SL and SR. In
Fig. 18. Storm propagation as described in Fig. 11, for the right- and left-moving storms which arise in association with the hodograph in Fig. 16.

In this framework, the left-moving storm travels faster than the low and middle level winds and to the left of all winds above about 1 km. In contrast, the weak cyclonic cell propagates at about the speed and direction of the environmental winds at 1.5 km.

The structure of the storm at 90 min is depicted by the horizontal cross sections presented in Fig. 19. The characteristics of the left-moving storm are similar in a mirror image sense to those of the right-moving storm discussed in the previous section. The principal downdraft is now located to the south of the updraft and spreads out to the north and west at the ground. Relative to the coordinate framework in the simulation, the left-moving storm is propagating to the east at about 3.75 m s⁻¹. The behavior of the weak cyclonic cell can also be seen in Fig. 19. Although it is noticeably weaker and shallower than its anticyclonic counterpart, it does produce a small amount of rain and some blocking of the environmental flow. The updraft in the left moving storm tilts to the southwest with height and contains a weak echo region at lower levels. Because of the mirror image similarity of this storm with the right-moving storm of the previous section, its features will not be presented in further detail.

5. Discussion

The long-lived storms simulated in the previous sections display striking similarities to the conceptual model proposed by Browning (1964). For a right-moving storm the downdraft is located along the left flank and outflow near the ground spreads out underneath the updraft, forcing continuous uplifting of the moist low-level inflow along the right flank. In this manner the storm maintains its moisture supply and tends to propagate to the right. In addition, these simulations suggest how the wind shear can determine whether a right- or left-moving storm will actually be produced by a particular sounding. As illustrated in Section 2, if the low, middle and upper level winds lie along a one-directional shear line, both right- and left-moving storms formed through splitting will have similar opportunities to establish a self-sustaining structure. Curvature of the wind hodograph appears to cause a relative enhancement of one of the downdrafts which in turn increases the gust-front-induced convergence beneath the storm. In particular, if the wind hodograph turns clockwise with height (Fig. 9) development of the right-moving storm is enhanced, while if it turns counterclockwise the left-moving storm is favored. The individual right- and left-moving storms simulated in Sections 3 and 4 arise through a splitting process in which the second cell decays due to an unfavorable orientation of middle level winds. As a result, observational verification of this behavior may prove difficult since if the secondary cell produces little or no rain it will not be detected by radar.

To further illustrate the influence of winds turning with height we consider the hodograph in Fig. 9 where the specified wind field produced a right-moving storm propagating according to the vector labeled SR. If a new hodograph is created which is a mirror image of the original about a straight line between the 0 and 4 km winds, the 2 km wind vector would be changed to the position denoted by the dashed vector and the new hodograph would turn counterclockwise with height. A numerical simulation with this new wind structure would produce a nearly mirror image left-moving storm propagating according to the heavy dashed vector labeled SL in Fig. 9. Relative to the assumed ground-based origin at this left mover propagates faster than the low and middle level winds. Thus, by decreasing the magnitude of the middle level wind vector in Fig. 9, conditions favorable for a right-moving storm can switch to support the left mover. In this manner gradual changes in the wind shear are seen to produce gradual and continuous shifting of the storm structure and intensity.

The results presented above suggest that the storm structure depends strongly on the curvature of the wind hodograph rather than on its orientation relative to the ground. For example, returning to Fig. 9, one could move the assumed ground-based origin anywhere on the hodograph without changing the simulated storm structure produced by the model (which neglects boundary layer effects). Only the propagation vector of the storm relative to the ground would change. Thus a cyclonically rotating storm, defined as a right mover based on its dynamics, could appear to propagate as a left-moving storm relative to the ground (and vice versa). This is illustrated in Fig. 9 by moving the
assumed origin \( \bigcirc \) to the location denoted by (3). Relative to this position, the right moving storm would propagate to the left of the winds at all levels. In this regard, perhaps it is the preferred orientation of wind profiles at midlatitudes in the Northern Hemisphere (low-level southerly flow turning to westerly with increasing height) which provides the strong correlation between storms which rotate cyclonically and storms which appear to propagate to the right of the mean wind.

Applying these concepts to observed soundings is complicated by numerous uncertainties in interpretation. Since the wind shear can vary dramatically in magnitude and direction with height it is often difficult to choose vectors which are representative of low, middle or upper level wind vectors. Further, the appropriate heights for these vectors may depend on the intensity of the storm which in turn is strongly influenced by the specific temperature and moisture profiles. Nevertheless, certain tendencies appear to exist in the wind shear associated with observed storms which are in agreement with our simulations. As described in II, observations of split storms in which both right- and left-moving storms remain strong arise in environmental winds which are often nearly one-directional (e.g., Charba and Sasaki, 1971; Brown, 1976). In contrast, the right-moving Geary and Wokingham storms have associated hodographs (see Browning and Donaldson, 1963) that turn clockwise with height. Similarly the hodograph corresponding to the left-moving storm studied by Hammond (1967) tends to turn counterclockwise. Other cases can be found where this behavior is not apparent, however, and thus further observational cases must be considered before the usefulness of this interpretation can be assessed.

In the simulations presented in the previous sections we have considered only the influence of the environmental winds on the structure and longevity of severe
storms; the initial temperature and moisture soundings have been held constant throughout. Clearly, these profiles are of considerable importance in establishing the intensity of a storm and in modulating the influence of a particular wind shear. In addition, boundary layer effects not presently included in the model may alter the propagation characteristics of a storm. It should be emphasized that although we have simulated self-sustaining single-cell storms, there is no evidence that other single-cell structures cannot exist which produce similar storm longevity. In particular, the storms simulated here evolve through a splitting process. For storms which do not split, other opportunities may arise for generating a self-sustaining structure. Also, as mentioned in the Introduction, storms which exhibit a deviate motion are often multicellular with propagation influenced by preferred locations for new cell formation. It is important to determine what changes are required either in the environment or in the model to simulate a multicell storm.

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REFERENCES