On the Movements of Convective Storms, with Emphasis on Size Discrimination in Relation to Water-Budget Requirements

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ABSTRACT

In typical squall-line situations wherein the wind veers strongly with height, individual convective storms move as much as 60 deg right or 30 deg left of the direction of the mean wind in the cloud layer. It is shown that, on the average, the radar echoes having largest diameters move farthest to right of the wind.

This behavior is consistent with physical considerations and with supply-and-demand requirements of the storm water budget. For a given rainfall intensity, the amount of water precipitated by a storm is proportional to its area or to the diameter squared. The amount of water vapor intercepted is proportional directly to the diameter, and to the velocity of the storm relative to the winds of the lower-tropospheric moist layer. A large storm must intercept more vapor in proportion to its diameter than a small one, requiring a larger migration velocity relative to the moist layer. This requirement is satisfied if (wind veering with height) large storms move toward the right of the mean wind.

Based on these considerations, a simple expression is derived for the direction of storm motion as related to storm diameter. This describes the mean behavior fairly well, but there is considerable residual scatter.

With this taken into account, an expression is given for the probability of storm passage over a given point as related to the initial storm location and size.

Some characteristic patterns of development are illustrated. New convective elements tend to form on or amalgamate with the right-hand side or end of an existing storm cluster or squall line, somewhat on the upwind side relative to the mean wind. This pattern of generation contributes to the movement of large storm clusters strongly toward the right of the winds, and also to make large storms move consistently more slowly than small ones.

1. Introduction

For purposes of air-traffic control, as well as for a large variety of human activities, it is desirable to have detailed short-period forecasts of the movements and patterns of development of thunderstorms. The locations, dimensions and intensities of such storms are specified by radar observations, but the changes observed with time are exceedingly complicated.

In this study, we attempt to filter out some of the characteristic features of storm movement and development, and outline a physical-statistical approach to forecasting storm occurrence at a given location.

2. Examples of variations in storm movement

Method of computation. Storm movements were determined from frequent sequential tracings of echoes. They pertain to the centers of highest reflectivity, from photographs of the scope of the WSR-57 radar at Oklahoma City. Generally, computations over periods of less than a half hour were considered unacceptable, and most computations are for much longer periods.

Because of the large space and time differences between routine upper-air soundings, the periods selected for study were only those when serial soundings (generally at 90-min intervals) were available in the convective region. Isogon-isotach charts were analyzed for the times of observations, and interpolated charts were prepared at hourly intervals. The wind direction and speed were then read off the nearest chart, at the exact location of a particular storm at the middle of the time period during which its movement was computed from the radar data.

The “mean wind” used in the comparisons was the
vector mean of the 850-, 700-, 500-, and 300-mb winds. This gives a fair approximation to the pressure-averaged wind in the 900-200-mb convective layer. Winds at individual levels were often severely disturbed due to the presence of a storm over the station or nearby. The influence of such disturbances is minimized when the mean wind is utilized. Where the "shear vector" is plotted, this is the 850-300-mb shear. It is more likely to be unrepresentative than is the mean wind, since it comprises a difference of winds at two levels, both of which may be disturbed in an opposite sense (see discussion by Fankhauser, 1964).4

To focus attention on the very considerable differences in behavior of individual storms, we have chosen to illustrate two successive days of pronounced thunderstorm activity over the Great Plains area.


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**Fig. 1.** Radar echoes at 1931 CST 3 May 1961, Oklahoma City WSR-57 radar. Range markers at 50 n mi intervals. Antenna tilt 0°, attenuations indicated at upper left. In lower figure, locations of storm cores shown at hourly intervals along tracks of selected storms (times labelled in CST).

**Fig. 2.** Mean of 850-300-mb winds, 1800 CST 3 May 1961. Solid lines, isotachs (kt); dashed lines, isogons at 10-deg intervals. Dashed wind symbols, 850-300-mb shear. Full barb is 10 kt; flag is 50 kt.

**Fig. 3.** Direction of echo-core movement vs. direction of 850-300-mb mean wind, 3 May 1961. Dots correspond to smaller echoes in N and E sectors of Fig. 1. Triangles correspond to squall-line cores in SW, blackened in for largest storms. A1, A2, and A3 show movement of echo A in Fig. 1 at successive times near beginning, middle and end of its life.

**Storm movements on 3 May 1961.** Beginning in the early afternoon of this day, there were numerous storms of relatively uniform size (often closely adjacent to each other, but distinguishable as individuals) mainly in the northeast quadrant from Oklahoma City. In late afternoon, a squall line formed in the southwest quadrant, over the Texas Panhandle. As shown by Fig. 1 the latter storms, which developed in a more unstable and moisture-rich air mass, were on the whole both larger and more intense than the others.

Winds in the convective area were southerly 20-30 kt near 850 mb, veering to approximately west 50 kt near the tropopause level. Fig. 2 shows the mean winds for the cloud-bearing layer. The 850-300-mb shear (dashed symbols) was from a northwesterly quadrant, reflecting the veering of wind with height.

The directions of storm movement are plotted against the mean wind direction at the location and time of...
Fig. 4. Configurations of radar echoes at approximately 20-min intervals, squall line of 4 May 1961. Attenuation levels marked at top, corresponding approximately to constant reflectivities except in second frame. Locations are relative to Oklahoma City, at intersection of E-W axis marked with time at bottom, and N-S axis which points toward upper left (see last frame for distance scale). The tracings are displaced successively toward 135°, approximately normal to squall line, so that successive tracings can be readily compared. Identifiable centers of higher reflectivity are labelled by English or Greek letters. Asterisks denote new cell formations.
Fig. 5. Mean wind fields at (a) 1200 CST and (b) 1800 CST 4 May 1961. Legend as in Fig. 2.
each storm, in Fig. 3. On the average, the smaller storms of the northeast quadrant (dots) moved somewhat to left of the winds; a fair correlation is evident between wind direction and storm movement. The behavior of the squall-line storms (triangles) was strikingly different, no such correlation being apparent. Several of these storms followed S-shaped tracks very similar to that of a storm described by Hoecker (1957). As in his example, these storms moved more nearly with the mean wind early and late in their lives when they were relatively small, but up to 60° to right of the mean winds when they were most strongly developed. There was also a tendency for appreciably slower migration velocity at the time of greatest storm size and intensity. This was particularly striking in the case of storm A. Its movement was from 220-230° at speeds of 14-26 kt during its growing and dissipating stages; while when the storm was largest, its average movement over a period of 4 hr was from 290° with a speed of only 6 kt.

Squall-line situation of 4 May 1961. The intense squall line shown in Fig. 4 developed near a fast-moving upper trough in the early afternoon of 4 May 1961. In the convective area, winds were southerly about 45 kt near 850 mb, veering to west-southwest about 60 kt near tropopause level. Potential instability was most pronounced in central Oklahoma, where there were numerous tornadoes and other severe weather occurrences in late afternoon. For detailed descriptions of individual storms, see Ward (1961), Hamilton, Donaldson, and Browning and Donaldson (1963). In addition to the squall line, there were many other storms, chaotically distributed, mainly southeast of Oklahoma City.

The 850-300-mb mean winds are shown, at 12C and 18C, in Fig. 5. Comparison of the isogon patterns or the individual reports discloses that even during a period as short as six hours, the wind changes may be quite large. This emphasizes the necessity for frequent soundings for research purposes, and for utilizing forecast wind fields at frequent intervals for storm movement prognoses.

Movement of echo cores within 150 n mi of Oklahoma City, during the 6-hr period between Figs. 5a and 5b, showed overall ranges of 100° in direction and 40 kt in speed. This was only in part due to the variability of the wind field. Some echoes moved as much as 33° to left of the mean wind direction while others moved up to 52° toward the right. As will be shown later, most of the storms moving to left of the wind were small, while those moving toward right were large.

One consequence of the differential movements of large and small echoes is illustrated in Fig. 4. At the first time, echoes H and G were located about 50 and 100 mi from the nearest storm core (A) on the southwest end of the squall line. Examining the successive tracings, it is seen that echoes G and H progressed toward the squall line, finally becoming incorporated into its southwest end. Convergence of echoes in this manner, due to the relative movement of either echo and H moving from a more southerly direction than the larger echoes in the squall-line proper, is commonly observed.

As found by the Thunderstorm Project (Byers and Brahm, 1949), individual echoes in a squall line characteristically move toward left of a normal to the line. Such a relative movement, which amounts in this case to a tendency for individual echoes to migrate from the southwest toward the northeast end of the squall line, is apparent in Fig. 4. Regeneration took place by a combination of new-echo formations on the southwest end of the squall line proper, and the accretion of originally isolated echoes such as those discussed above.

3. Physical analysis of the problem

Among the factors which may influence the patterns of development and migration of convective storms, are the distribution of stability and moisture, and the fields of divergence and vertical motion, both as imposed from external sources and as generated by the convection itself. Because of the paucity of upper-air observations, these influences cannot generally be analyzed in the detail required to appraise their effects on an individual storm. What remains is to study the movement of a storm in relation to the wind field in its surroundings.

Humphreys (1940) suggested that convective clouds should move with the mean wind in the cloud layer. Studies of radar-observed convective storms, by H. B. Brooks (1946), the Thunderstorm Project (Byers and Brahm, 1949), Ligda, Hiser and Bigler, and Kotov and Khe Zhui-Tszyun (1961), have indicated that this was nearly true on the average.

For the most part, these studies have intentionally been concerned with relatively small storms, whose movements were uncomplicated by the influences of propagation (new cell development). By contrast, studies by Byers (1942), Hoecker (1957), Hamilton (1958), Newton and Katz (1958), and Newton and Newton (1959) indicated that large thunderstorm clusters, such as those in squall lines, move systematically with an appreciable component toward the right of the upper winds.

In the cases discussed in the preceding section, as in the great majority of severe convective cases over the Great Plains regions, the wind veered strongly with height. Fig. 6 is a sketch of a thunderstorm in such an

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environment. If the air within the storm were drawn in equal quantity from upper and lower levels, and mixed vertically by the updrafts and downdrafts, the mean horizontal motion inside the storm would correspond to the mean of the environmental winds, through the layer in which the storm is imbedded. If, as is more realistic, most of the in-cloud air originates in the lower levels, the motion of the in-cloud air must be biased toward the velocity of the lower levels (as noted by H. B. Brooks, 1946). By this consideration, a storm in which propagation plays a minor role should move toward left of the mean wind velocity, when the wind veers with height.

Newton and Newton (1959) have described a mechanism by which generation of new convection is favored on the general downshear flank of a convective storm (right-hand flank in Fig. 6, relative to the mean wind in the cloud layer). This mechanism depends on an interaction between environmental winds and in-cloud winds, which at individual levels have differing velocities. Analysis of the forces involved showed that the magnitude of this influence increases with the storm diameter. Thus the tendency for a storm to move to the right of the mean wind (or a smaller amount to the left), as a result of new convective growth on its right flank, should be greatest when the storm diameter is large and the veering of wind with height is strong.

A parallel consequence of the relative motions illustrated in Fig. 6 is that fresh water vapor is continually supplied to the right-hand flank of the cloud system, in the lower levels where moisture is most abundant. As suggested by H. Weickmann (1953), the persistence of a convective storm depends on its migration velocity relative to the moist labile air of the lower levels. The presence of vertical shear and consequently of such relative motions, as in Fig. 6, results in continuous replenishment of the water rained out and that carried away in the various branches of the storm circulation.

Storm movement in relation to moisture budget. A simple expression relating the direction of movement of a convective storm to the shear in the environmental wind field can be readily derived. This will be done for a special case which is easily handled.

The model of moisture flow utilized is illustrated schematically by Fig. 8, a vertical section along line AA' of Fig. 7. The environment consists of a lower moist layer surmounted by a dry upper layer of equal depth. The relative motions of outside air with reference to the storm motion are indicated by $\mathbf{V}_{RL}$ and $\mathbf{V}_{RU}$ (means for the layers), according to the scheme in Fig. 6.

The heavy arrows in Fig. 8 correspond to moisture fluxes through the boundaries of the cloud system. $M_1$ represents the amount of water vapor intercepted by the storm due to its relative motion, and $M_2$ the loss of water through precipitation. $M_3$ represents the cumula-
tive loss due to condensation into cloud droplets which remain aloft, together with advective and evaporative losses at other portions of the storm boundary. According to continuity,

$$M_1 = M_x + M_s. \tag{1}$$

Computations by Braham (1952) and Newton (1963) suggest that, of the water vapor that participates in the storm circulation, the proportion that reaches the ground as rain amounts to only about 10 per cent for a small storm, or perhaps 50 per cent for a large one. While not directly comparable to Fig. 8, these computations suggest that $M_g \ll M_1$. The simplest assumption that can be made is that there is some typical partition between $M_2$ and $M_3$ of Eq. (1), such that

$$kM_1 = M_2. \tag{2}$$

Here $k$ is a catch-all coefficient ($0 < k < 1$) expressing partly the real efficiency of the storm as a rain producer, and partly the effectiveness of the ventilation due to the vertical shear and to the motion of the storm through its environment. There is no a priori justification for supposing that the "ventilation efficiency" $k$ is a constant for different storm sizes; this will be remarked upon later.

The wind is assumed to veer 90° between a lower level ($V_L$) and the top of the storm ($V_U$), with a linear hodograph, $V_L$ and $V_U$ being equal. The storm velocity, $V_S$, is assumed to lie somewhere between $V_L$ and $V_U$ (Fig. 9).\footnote{It is noted later that large storms characteristically move more slowly, while some small storms move faster than the mean wind speed. Eq. (3) is therefore an approximation, which however is not bad when the storm speed does not depart by more than 30–40 per cent from the mean wind speed.}

If $\tilde{R}$ is the mean precipitation per unit time, over the area covered by the storm, then

$$M_2 = \tilde{R}aD^2/4. \tag{6}$$

Eqs. (5) and (6) may now be combined with the aid of Eq. (2) to yield, after some rearrangement,

$$\tan \alpha \approx \frac{1}{\sqrt{\frac{kSg\pi D}{4kq\Delta p}}}. \tag{7}$$

It is convenient to define a critical diameter $D_0$, corresponding to a storm which moves along the mean wind direction. Setting $\alpha = 0$ in Eq. (7),

$$D_0 = \frac{kSg\pi D}{4kq\tilde{R}}. \tag{8}$$

On substitution of this into Eq. (7), we obtain

$$\tan \alpha \approx \frac{S/\pi D}{4\tilde{R}/D_0}. \tag{9}$$

For the purpose of illustration, the following values may be adopted: $S = 28$ m sec$^{-1}$, $\tilde{V} = 14$ m sec$^{-1}$, $q = 6.$

From Fig. 9,

$$\tilde{V}_{RL} = \frac{S}{4} + \tan \alpha. \tag{3}$$

From the hydrostatic equation, the water-vapor content of a column of unit area in the moist layer is $q\Delta p/g$, where (Fig. 8) $\Delta p = p_0 - p_m$. In unit time, the amount of water vapor intercepted by the storm within the moist layer is then, from Fig. 7,

$$M_1 = \tilde{V}_{RL}D \cdot q\Delta p/g, \tag{4}$$

where $D$ is storm diameter. On substitution from Eq. (3),

$$M_1 = \frac{\left[(S/4) + \tilde{V} \tan \alpha \right]}{\tilde{V}} = \frac{q\Delta p}{g}. \tag{5}$$

Fig. 8. Components of water budget of storm in sheared environment. See text.

Fig. 9. Simplified wind field in storm environment. See text.
gm kg\(^{-1}\) = 6\times 10^{-4}, \Delta p = 400 \text{ mb} = 4 \times 10^4 \text{ gm cm}^{-1} \text{ sec}^{-2}, \\
\bar{R} = 1 \text{ cm rain per hr} = 2.8 \times 10^{-4} \text{ gm cm}^{-2} \text{ sec}^{-1}, D_0 = 15 \\
\text{km. With these values, Eq. (8) gives}

\begin{align*}
k &\approx 0.2
\end{align*}

which can be regarded as only a rough estimate. With the prescribed wind field, according to Eq. (9) a very small storm \((D = 0)\) would move as much as 27° to left of the mean wind, while a storm of diameter 30 km \((D = 2D_0)\) would move 27° to right. This difference in behavior is necessary to satisfy supply-and-demand requirements for water vapor. According to Eq. (6), the demand for moisture is proportional to the square of the diameter. Eq. (4), on the other hand, sets the amount of vapor intercepted directly proportional to the diameter only. For a large storm, which precipitates a large mass of water relative to its diameter, \(\bar{V}_{RL}\) in Eq. (4) must therefore be large. This condition is met, according to Fig. 9, if the large storm moves more toward right of the mean wind than does a small one.

The step from Eq. (7) to Eq. (9) presupposes that the quantity on the right side of Eq. (8) is invariant. This supposition may be justified for all the factors except \(k\) and \(\bar{R}\), since the other factors are specified by the physical structure of the environment. Thus, in treating \(D_0\) as a constant, it is in effect presumed that \(k \approx \bar{R}\). While qualitative arguments can be advanced for the notion that both \(k\) and \(\bar{R}\) increase with storm size, these do not prove that \(k/\bar{R}\) is a constant for a given storm situation. It may be noted, however, that if this is not approximately true, Eq. (9) should fail when tested against real data.

In the interest of simplicity, Eqs. (8) and (9) were

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**Fig. 10.** Wind observation at Ardmore, Okla., 1715 CST 21 May 1961. Dots correspond to end-points of wind vectors at 50-mb intervals. \(\bar{V}\) is mean wind for whole layer 950–200 mb; \(\bar{V}_L\) is mean for moist layer. For explanation of other symbols, see text.

**Fig. 11.** Echoes from Oklahoma City WSR-57 radar, 1529 CST 21 May 1961. Range markers at 20-n mi intervals. Antenna tilt 0°; attenuation at upper left.
developed for the special geometric assumptions embodied in Figs. 7-9. An example of the wind distribution in a real situation is shown in Fig. 10. This is a holograph of an observation about 100 n mi southeast of the squall line shown in Fig. 11. Here \( \vec{V}_L \) was taken as the mean wind between 950 mb (near the surface) and the top of the moist layer (670 mb). The vector \( \vec{V} \) is the mean wind through the layer 950-200 mb. If \( \theta \) is the angle between \( \vec{V}_L \) and \( \vec{V} \), we define

\[
S' = \frac{\vec{V}_L \sin \theta}{\vec{V}}, \quad \vec{V} = \frac{\vec{V}_L \cos \theta}{\vec{V}}.
\]

Also, it is reasonable to suppose that a moving storm, like a stationary one, may draw moisture from some distance away, due to convergence of lower-level winds toward the storm. It may, for example, be assumed that the storm in effect sweeps up the water vapor in a swath of width \( D + \delta D \), greater than the diameter \( D \) of the rain area. With these more general conditions, a derivation similar to that leading up to Eq. (9) gives the more general form

\[
tan \alpha = \frac{S'}{\vec{V}} \left[ \left( \frac{D_0}{D} \right)^2 \left( \frac{D_0 + \delta D}{D + \delta D} \right) - 1 \right].
\]

Note that Eq. (9) is only a special case of Eq. (10), for the particular assumptions \( \delta D = 0 \), \( S' = S/4 \), and \( \vec{V} = \vec{V}_L \).

Test against actual cases. The situation of 21 May 1961 is well-suited for a test of the simple expression developed above, since there was a broad spectrum of observed storm sizes and particularly good radar coverage was recorded. On the afternoon of this day, an open frontal wave was centered over central Oklahoma, with maximum potential instability over central and eastern Oklahoma. Fig. 10 is typical of the average upper-wind conditions in the vicinity of the convective activity for this case.

Precipitation echoes in mid-afternoon, as shown by the Oklahoma City WSR-57 radar, are illustrated at three attenuations in Fig. 11. The squall line was at that time already well-developed in the northwest quadrant, and there were several other giant storms farther east which showed no particular pattern of organization.

The deviation of storm direction, to right or left of the mean wind direction, is plotted against storm diameter in Fig. 12. This sample includes all storms whose movements could be reliably tracked, within 130 n mi range of Oklahoma City between 1405 and 1915 CST. It should be noted that here “storm diameter” is a relative measure, being the greatest median diameter achieved by the radar echo during the period of velocity measurement for a given storm. Such computations were made over periods when the echoes did not change conspicuously in size. For this sample, the most satisfactory continuity was provided by 30-decibel attenuation, for which the reflectivity “Z” at 50-mi range was about \( 10^5 \text{ mm}^3 \text{ m}^{-3} \). These are plotted as dots in Fig. 12, along with the regression lines (of \( y \) on \( x \), and \( x \) on \( y \)).

Storm movements varied between 36° left and 57° right of the direction of the mean wind. Movements of individual “hard cores” were quite persistent over periods of 1 to 2 hr, except in storms which changed radically in size. An example is echo B, which developed east of the squall line. During the first 110 min of its life when the diameter of the 30-db contour averaged 8 mi, this storm moved on the average 20° to left of the mean wind. During the next 80 min when it reached a diameter of 15 mi and showed a “hook,” its movement averaged 15° to right of the wind. Its average speed diminished from 23 to 14 kt between these two periods. Another storm showing the same behavior is echo C; the storms of 3 May 1961 (Fig. 3) acted in a similar fashion. The giant storm E (Fig. 11), which was the largest and most intense of the day, also moved farthest to right of the winds.

The correlation coefficient between echo size and deviation from mean wind direction is 0.80. The scatter is magnified by uncertainties in wind measurements and analysis, as well as errors in measurements of echo sizes and the lack of range correction in the radar attenuation. In addition, according to Eqs. (8) to (10), variations in the physical environments of different storms should cause them to move in different modes.

In the general area of the storms, the mean top of the moist layer was found to be about 650 mb. The fields of \( \vec{V}_L \) (for the layer 950-650 mb) and \( \vec{V} \) (for the layer 950-200 mb) were analyzed, and mean values of \( S' \) and \( \vec{V}' \) (Fig. 10) estimated for the area and period encompassing the storm sample.11

These mean values were utilized, along with the observed \( D_0 \), to construct the dashed and dotted curves in Fig. 12, according to the theoretical relationship of Eq. (10). The fit is satisfactory, considering the crudity of the assumptions and the above-noted sources of error in the data.

The relationship is tested in Fig. 13, for the case of 4 May 1961 discussed in Section 2. In this sample, because of the great variation in ranges of individual storms, an attempt was made to minimize the influence of range attenuation on sizes of echoes.12

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9 See footnote 9. Eq. (10) is only a reasonable approximation when \( \vec{V}' \) is not greatly different from \( \vec{V} \). This condition is not always satisfied. It is not clear at the present time, however, how a more general expression can be derived.

10 The “top” of the moist layer was taken as the level where the most significant break in the dew-point lapse rate occurred. Where this was ambiguous, the choice was guided by conditions at neighboring stations. Within a moderate range, the exact choice of the top of the moist layer is not critical. An overestimate of the depth of the moist layer leads to an overestimate of \( \Delta \rho \), but also an underestimate of \( S' \) which tends to compensate.

11 The range intervals and the corresponding attenuations used are: 20-70 n mi, 30 db; 80-100 n mi, 24 db; 110-150 n mi, 18 db; and >150 n mi, 12 db. In these range intervals, the reflectivities of the contour edges were approximately 2 to 5 \( \times 10^5 \text{ mm}^3 \text{ m}^{-3} \).
Fig. 12. Deviation of storm motion from direction of mean wind, vs. echo diameter, for storms of 21 May 1961. See text.

Fig. 13. Same as Fig. 12, for storms of 4 May 1961.

Fig. 14. Storm speed minus speed of mean wind, vs. echo diameter. On abscissa, negative values correspond to storm movement slower than wind speed.
From the serial soundings, it was determined that the mean top of the moist layer was near 700 mb. The ratio $S' / W'$ in Eq. (10) was extremely variable in this case, and it was impossible to assign a value of this quantity at individual storm locations. The appropriate value appears to lie somewhere between 0.45 and 0.9, with a mean value over the area of about 0.6. The theoretical curve for $S' / W' = 0.6$, and for $\delta D = 0$ in Eq. (10), lies close to the line of best fit for the data. The correlation coefficient for this sample is 0.66.

The degree to which Eq. (10) fits is encouraging to the viewpoint that useful quantitative relationships might be developed, based on water-budget and other physical requirements. It should be noted that, although a quantitative analysis is given above for only two storm samples, the storm behavior in all other situations examined was in qualitative agreement with the principles developed above.

The complicated structures of storms and our inadequate understanding of them impose a limit on the success which might be achieved by a purely physical approach. A statistical survey of a much more extensive sample is needed. Among other things, this would probably reveal some fairly constant value of the diameter $D_0$ in Eq. (10), obviating knowledge of the characteristic values of all the quantities entering into the right-hand side of Eq. (8). The role of statistics lies further in determining the degree of scatter of storm behavior about any theoretical relationship that might be developed.

**Speed of storm movement.** For the case of 4 May 1961, the deviation of storm speed from mean wind speed is plotted against storm diameter in Fig. 14. This illustrates a tendency (correlation coefficient $-0.57$) for the largest-diameter storms to move most slowly. The corresponding scatter diagram for the case of 21 May 1961 (not shown) is very similar.

In these two cases, and in three others in which sizes were estimated less quantitatively (all five being cases with a marked veering of wind with height), storms were grouped into “small” and “medium” size categories, about 5 to 10 mi diameter, and “large,” about 15 mi diameter or larger. On the average, small- and medium-sized storms moved 2-3 kt slower than the mean wind. Large storms, however, averaged 13 kt slower than the speed of the mean wind (which itself averaged 40 kt for the five cases). Statistics for all five cases indicate that a tendency to move slowly goes hand-in-hand with the prediction for large storms to move toward right of the winds, when the wind veers significantly with height.

4. **Patterns of development, and influences on overall movement of storm complexes**

The influences treated above are discussed in the context of behavior of individual “storms” or centers of higher reflectivity observed by radar. It is generally not possible to discern the details of the growth processes affecting the movements of an individual storm, because of the limited resolution of the radar. When groups of storms are considered, however, it is possible to examine the patterns of growth and dissipation. It is evident that, if there is a systematic pattern of development, the movement of a storm complex will be different from the movements of its constituents. The main features of some examples will be mentioned here; these are analysed in more detail elsewhere.3

**Large storms of 24 May 1962.** On occasion, massive convective storms are observed which do not have the same degree of organization as squall lines, but which produce equivalent damaging weather over more restricted areas. Two such giant storms, accompanied by numerous smaller ones, were observed over Oklahoma on 24 May 1962.

The wind veered from southerly about 30 kt at 850 mb, to westerly 50-60 kt near the tropopause. Outlines of one of the two principal storm clusters, at hourly intervals, are shown in Fig. 15. During the times when the clusters were largest, they moved 40-50° toward right of and with about half the speed of the 850-300-mb mean wind.

Storm B and the smaller storm a, which were close neighbors at 1401 C, had such widely divergent tracks that three hours later they were separated by 80 mi. Storm a remained throughout as an identifiable single echo core, moving slightly to left of the mean wind. Storm B, however, developed into a large aggregate consisting of six to ten cores of maximum radar reflectivity. The structure continually evolved, the storm cluster being dominated at different times by different radar “cells.”

The average movement of the internal cells was about 15° to right of and at about 80 per cent of the mean wind velocity. The storm as a whole, when it was largest, deviated 40° farther toward right and moved with only slightly more than half the mean cell speed. Thus the individual cells migrated through the storm cluster, from the general upwind side toward the downwind side. During a 5-hr period examined in detail, new cells formed only in the upwind (southwest) half of the storm. Although as many new cells formed in the left upwind quadrant as in the right quadrant, those in the right quadrant achieved greater size and intensity. These patterns of formation of cells account for the way the storm moved, far to the right of and much slower than the individual cells.

The plot of storm cell movement relative to wind direction and speed was similar to that shown in Figs. 12-14. However, Eq. (10) gave a large overestimate of the storm deviation from wind direction. The reason for this is not understood; a contributing factor may be

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that the hodograph was very dissimilar\textsuperscript{10} to that in Figs. 9 and 10 (\( \mathbf{V} \) was more than twice as large as \( \mathbf{V}' \)).

\textit{Storm complex of 5 May 1961.} On this day, the wind veered only moderately with height but the upper winds were quite strong. The available soundings indicated greatest potential instability in south central Oklahoma (the lifted index at Fort Sill was \(-8^\circ\)). A large and intense multicellular storm, the simplified outlines of which are shown at hourly intervals in Fig. 16, formed in this region. There were also extensive patches of convective activity, mainly east and northeast of Oklahoma City (in less unstable regions), which were characterized by numerous small- to medium-sized cores of fairly weak radar reflectivity.

The 850-300-mb mean wind was from south-southwest 50-60 kt. The patches \( B \) and \( C \) of medium-sized storms showed movements of 10 to 20 kt to right of the wind, but also only about this much movement along the direction of the mean wind (individual cells moved on the average along the mean wind). Since the mean speed of the individual echoes was 46 kt, this indicates that new echoes formed mostly on the south sides of the convective patches, migrated through them, and dissipated on approaching their northern boundaries.

A partial history of the development of the large storm \( A \) south of Oklahoma City is provided by the echo tracings in Fig. 17. New strong cells developed successively on its southwest (upwind) end; cells farther northeast gradually dissipated. All of these cells
moved toward right of the mean wind (on the average, by about 15°) and at about half the mean wind speed. Storm cluster A as a whole (Fig. 16), however, moved even farther to right of the winds and, as in the case of Fig. 15, much more slowly than the individual cells. Between 1225 and 1537 CST (Fig. 17), new cores formed at intervals of about 40 min, at distances averaging about 10 n mi from the cores previously occupying the southwest end of the storm complex. The formation of these new cores resulted, in effect, in an upwind component of motion of this end of the storm, amounting to about 15 kt. When added vectorially to the mean motion of the individual cells (24 kt from 248°), this gives an overall storm motion of 13 kt from 280° (Fig. 16).

**Summary of behavior of squall-line echoes.** Based on the cases discussed in this report (e.g., Figs. 4 and 11), and a larger number of film records inspected, the schematic Fig. 18 has been sketched. This is intended only to show the most general aspects of squall-line structure. Although a single line of echoes is indicated here, there may in some cases be a more complex “squall-line zone” consisting of more than one line, as described by the Thunderstorm Project (Byers and Braham, 1949). As discussed by Boucher and Wexler (1961) and by Fankhauser (1964), one or the other of these lines may dominate at a given time, and their formation or dissipation may strongly influence the movement of the zone as a whole.

New cells are most likely to form within 10-15 mi of the “upwind” end of an existing squall line at 20- to 40-min intervals, under typical conditions of fairly strong winds aloft which veer with height. Under these conditions, a movement of individual echoes to left, nearly along, or to right of the mean wind may take place, depending on the echo size as indicated on the right side of the figure. Large storms, which deviate farthest to right, also usually move appreciably slower than small ones.

Considering the typical orientation of squall lines relative to the mean wind direction, a storm which forms on the “upwind” end migrates toward the left end with respect to the direction of advance of the line. The cells on the “downwind” end are generally the oldest, the ones most likely to be approaching the dissipating stage, and the ones with the broadest anvils.

In the case of cell clusters which are not formed in distinct lines, the most likely region of formation of new echoes is the upwind side relative to the mean wind in the cloud layer; the cells which are most likely to achieve greatest development are those on the right-hand side of the storm track. Multicellular storms are not static in structure; rather the cell structure continually evolves with individual cells migrating through the storm. Thus if by means of radar the movement of an individual center of high reflectivity is determined, it should be recognized that this may differ considerably from the movement of the storm cluster as a whole. As shown by Browning and Ludlam (1963), a given storm may at one time be multicellular, and at another time when it is more severe it may be in “steady state” rather than being characterized by sporadic cell development.

In the cases of both irregular storm clusters and squall lines, the pattern of new-echo formation is such as to cause the echo complex, as a whole, to move farther toward right of the upper winds, and slower than the individual storms or cells making up the complex.

When the wind does not veer with height, the above generalizations do not all apply. For a detailed description of squall-line behavior under conditions of little wind veer with height, see Fankhauser (1964).

5. **Forecasting probability of passage of an individual storm**

In estimating the probability of passage of a convectional storm over a given point (such as an air terminal or a point on an airway), two basic pieces of information are needed:

1. The most likely direction of motion of the storm, or the “expected path.”
2. The degree of variation of storm movements about the “expected path.”

Provided a storm does not change size markedly during the forecast period, the direction of its expected movement may in principle be computed from Eq. (10). Data on the degree of scatter about the expected path can only be established empirically. Based on six synoptic situations in which storms were categorized only as “small,” “medium,” and “large,” the average standard deviation of storm motion about the mean for each category was 9° to 16°. Obviously this would become smaller if a continuous rather than discrete size representation were utilized.

For the general case wherein the forecast point A lies an arbitrary distance d “downwind,” and a distance L to right of or left of the expected path, the geometry pertinent to probability determination is shown in Fig. 19. To pass over A, the storm must move somewhere between directions α1 and α2. For d appreciably larger than L, we may write

$$\tan \alpha_1 = (L + D/2)/d; \quad \tan \alpha_2 = (L - D/2)/d.$$  \hspace{1cm} (11)

A study of the frequencies of storm directions of movement suggests that these are distributed in approximately a normal fashion about the expected path. We define $\beta = \alpha - \sigma_p$, where $\sigma_p$ is the standard deviation of direction of motion for a given storm size.

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Fig. 18. Simplified sketch of principal features of a typical squall line. Solid lines show precipitating cloud (regions of heavier rain cores hatched); dashed lines the general anvil outline (which may be smaller or more extensive depending on the age of the squall line). New cell formation is most likely inside dotted boundaries, but may occur elsewhere. Inset shows most typical environmental winds, veering between lower ($V_L$) and upper ($V_U$) levels, and characteristic movements of storms of different sizes relative to vector mean wind.
Then the likelihood of a storm moving in a direction between \( \alpha_1 \) and \( \alpha_2 \) may be expressed by use of the probability integral,

\[
P = \frac{1}{\sqrt{2\pi}} \int_{\beta_1}^{\beta_2} e^{-\beta^2/2} d\beta.
\]

(12)

The limits of integration are, from Eqs. (11),

\[
\beta_{1,2} = \frac{\arctan[(L \pm D/2)/d]}{\sigma_D}.
\]

(13)

Values of \( \beta \) are easily computed for assumed values of \( L, D, d \) and \( \sigma_D \), and the probability \( P \) in Eq. (12) can be evaluated from standard tables (e.g., Larsen, 1948).

For an assumed \( \sigma_D = 15^\circ \), and storm diameter 5 n mi, a sample nomogram is given in Fig. 20. The probability of storm passage may be read off opposite the intersection of the appropriate lines \( d \) and \( L \). It may be noted that, in the cases studied, the extreme range of storm direction was approximately \( \pm 2\sigma_D \) about the modal direction for each size category. With use of Eqs. (12) and (13), the curves of Fig. 20 may be readily extended.

In many situations, the forecast point may lie in a position vulnerable to either of two or more storms. According to probability theory (see, e.g., Anderson and Bancroft, 1952), if \( P(A) \) and \( P(B) \) are the individual probabilities of storms \( A \) or \( B \) passing, then the probability of \( A \) and/or \( B \) passing is

\[
P(A + B) = P(A) + P(B) - P(A)P(B).
\]

For example, suppose that the expected paths of two storms lie near the point for which a forecast is desired, and it is determined that the probabilities of passage of the individual storms are 60 and 40 per cent. Then the probability of one or both passing is 76 per cent.

Timing of storm arrival. If \( d \) is the distance of a storm from a point it is expected to strike, the forecast time of arrival \( T_F = d/V_F \), where \( V_F \) is the forecast storm speed. Denoting the actual speed by \( V_f + \epsilon_s \) where \( \epsilon_s \) is error in forecast speed, we find the error in timing of storm onset to be

\[
\epsilon_t = \frac{d}{V_f + \epsilon_s} = \frac{d}{V_f} - \epsilon_s.
\]

(14)

From a study of six synoptic situations, the standard deviation of storm speeds relative to the average speed for given storm size categories was found to be about 7 kt. Inserting this value in place of \( \epsilon_s \) in Eq. (14), we find that for a storm 60 mi distant from a point in its expected path, the time of arrival can be forecast (\( \frac{3}{4} \) of the time) within an accuracy of \( \pm 7 \) min if the expected storm speed is 60 kt, or \( \pm 28 \) min if the speed is 30 kt.

Fig. 19. Illustrating the probability of a storm moving over a point an arbitrary distance \( d \) distant, and a distance \( L \) to one side of the expected path. See text.

6. Conclusion

This study has established that there is a systematic variation in the movement of storms, in accord with expectations from physical considerations. There is also a great deal of random departure from the modal behavior. Indications are that the forecasting of individual storm movements must depend on a combination of physical considerations and statistical-empirical findings. The examples demonstrate that ideally each storm should be treated as an individual, since different storms under the same environmental conditions may move in different ways.

With recent technical advances, possibilities are greatly enhanced for dealing effectively with the vast amount of data measured by radar, in order to provide detailed forecasts from these data. The automatic data processing system STRADAP (Atlas, Sweeney and Landry, 1963), which computes and maps reflectivity and cloud-top information, is an important step forward. Kessler and Russo (1963) have devised a scheme whereby, in addition, an electronic computer may work out autocorrelations of the radar-scope patterns at successive times. This system would provide an extrapolation of the mean motion of the echo pattern as a whole, along with information on the dimensions of systems and their development. The use of a physical-statistical method such as outlined in the present paper would serve to give more specific estimates for particular locations such as air terminals.

In extending the findings of this study, use should naturally be made of data from calibrated radars equipped with sensitivity-time-control (such as are being gathered routinely by the Weather Bureau National Severe Storms Laboratory). In the accumulation of statistics relating storm movement to the wind field, it is moreover essential that frequent soundings be made, preferably with a special network much more dense than the regular aerological network.

We have discussed storm movements only in relation to storm size. It is quite likely that other parameters
Fig. 20. Nomogram for probability of a storm of diameter 5 n mi passing over a point, assuming standard deviation of echo direction of movement (relative to mode for size category) is 15°. See text. This nomogram is valid for any storm diameter \( n \times 5 \) n mi, provided \( d \) and \( L \) are also multiplied by \( n \).
relating to storm intensity are also appropriate. Finally, it should be stressed that the most baffling problem in dealing with convective systems is that of predicting the persistence of existing storms and the locations where new storms may be expected to form. Only some very general indications have been given here, in relation to the latter, and this aspect of storm behavior is deserving of much further study.

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