HODOGRAPHS AND SEVERE WEATHE

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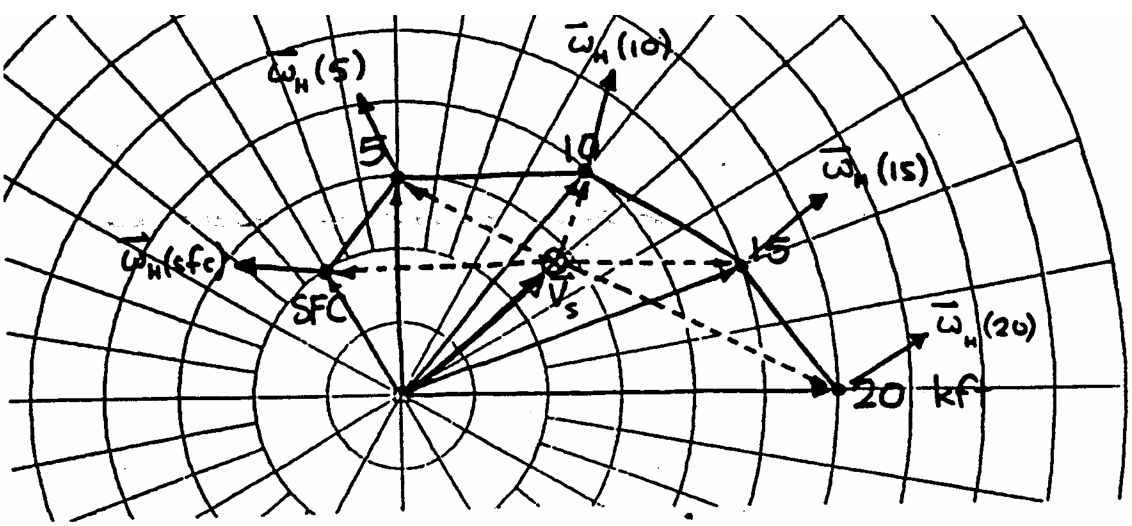
One ingredient which is believed to be important in governing the morphology ofthunderstorms is the profile of vertical shear in the environment which supports the storms. Numerous observational and theoretical studies have shown that storms which form in weakly-sheared environments tend to have non-steady circulations (multicells), while those that form in strongly-sheared environments can develop steady, persistent circulations (supereells). Although intuition suggests that strong shear can only inhibit the formation of organized updrafts, this tendency is partly offset by the ability of shear flows to generate a variety of hydrodynamical instabilities which allow for the possibility of updraft growth. Forecasters who work in areas of the country prone to outbreaks of severe weather should be prepared to recognize not only the thermodynamic conditions but also the vertical shear conditions favorable for various types of severe storms. Inspection of temperature and moisture soundings can reveal the presence of the necessary thermodynamic instability, while inspection of wind profiles (hodographs) can help diagnose whether conditions are right for the development of tornadoes. Hodographs can be drawn either as plots of u (z) vs. v (z) in Cartesian coordinates or V (z) vs. 8 (z) in cylindrical coordinates. In either case, the actual shape of the hodograph will be the same for any given wind profile. On the OU Meteorology weather computer, hodographs from any raob station may be plotted using "mchodo" in GEMPAK. Each plotted hodograph represents nothing more than the curve which connects, in order of ascending altitude, the tips of all the observed wind vectors from a sounding, with the bases of the vectors attached to a common origin. An example of a simple hodograph is shown below; the assumed wind profile is:

z(kft)	θ (deg)	V (kt)
0	150	10
5	180	15
10	220	20
15	250	25
20	270	30



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Note that the wind vectors appear oriented exactly as they would if drawn on a map; a south wind (from 180 deg) points due north, and a west wind (from 270 deg) points due east.

The familiar relation between the thermal wind and temperature advection dictates that die geostrophic wind veers with height when warm advection occurs and backs with height when cold advection occurs. Thus patterns of warm and cold advection can readily be diagnosed on hodographs. The influence of surface friction, which causes surface and boundary layer winds to be subgeostrophic and thus to blow across pressure contours toward low pressure, can also be readily seen in most hodographs. It causes most hodographs to display low-level veering regardless of what type of thermal advection is taking place. Most hodographs become somewhat chaotic and "noisy" at high altitudes; this is because the amount of error in rawin-derived winds increases when the balloon is far away from the launch point. It turns out that, for the purposes of forecasting severe storms, we need only consider the form of the hodograph in the lower troposphere. We will be interested not only in the strength of the winds and the presence of thermal advection, but also in the curvature of the hodograph and the expected or observed storm motions.

The orientation of the vertical shear vector $\partial\vec{V}/\partial z$ at any level in a sounding can be found by inspection of the hodograph. Because the hodograph is simply a curve connecting the sequence of wind vector tips in the sounding, the vertical shear in the layer between two wind obs i and j:

$$\left(\frac{\partial\vec{V}}{\partial z}\right)_{i-j}=\frac{\vec{V}_i-\vec{V}_j}{z_i-z_j}$$

will always be aligned with the vector line segment connecting the wind vector tips at levels i and j. <u>Thus the vertical shear vector at any level is tangent to the hodograph at that level</u>. For example, the vertical shear vector in the layer lying between 5000 and 10000 ft in the sample hodograph shown earlier points from about 270 deg. Now in a pre-storm environment where vertical velocities are negligible, the vertical shear $\partial\vec{V}/\partial z$ implies the existence of a horizontal vorticity $\vec{\omega}_H$. This horizontal vorticity vector is given mathematically by:

$$\vec{\omega}_H=\hat{k}\times\frac{\partial\vec{V}}{\partial z}=\frac{\partial u}{\partial z}\hat{j}-\frac{\partial v}{\partial z}\hat{i}$$

where horizontal variations in vertical velocity have been neglected. Thus $\vec{\omega}_H$ <u>always points perpendicular and to the left of the hodograph curve.</u> In the earlier example, the horizontal vorticity (OH in the layer from 5000 to 10000 ft points from 180 degrees.

An additional important use of hodographs is the construction of profiles of storm-relative winds. To obtain the storm-relative winds from the observed winds, a storm motion $\vec{V}_s$, must either be measured (say, by radar) or predicted. In general, storm motions do not have to lie on the hodograph, nor do they have to conform to the mean winds in the environment. However, they are usually reasonably close to the mean winds in the environment. Once storm motion is specified, then the storm-relative wind profile is obtained from the vector differences:

$$\vec{V}_r = \vec{V} - \vec{V}_s$$

Note that this operation simply shifts the origin of the storm-relative hodograph to the tip of the storm motion vector. For instance, in the sample hodograph given earlier, storm motion is indicated hypothetically with an encircled X. The storm-relative wind vectors (see dashed vectors) run from this new origin to the various points of the original hodograph. For example, the storm-relative surface winds in the sample hodograph are from the east. Note that the hodograph looks exactly the same.

Severe thunderstorms generally form when the environment contains both strong thermodynamic instability and strong vertical shear, assuming some mechanism is available to trigger the convection. Observations and numerical studies suggest that when the vertical shear is relatively weak compared to the instability, the resulting storms, although possibly severe, will probably be multicellular. Such storms generally produce heavy rain and strong straight-line winds, and possibly some hail. Tornadoes and giant hail, on the other hand, most often occur in conjunction with supercell storms. These storms occur when the vertical shear is strong relative to the thermal instability. Later we will give a quantitative way of estimating whether the relationship between the shear and the instability is favorable for supercells.

The hodographs associated with supercell development usually show "strong" shear, with the shear-vectors remaining either unidirectional with height or veering with height. "Strong" shear is present if the magnitude of the vector difference between the boundary layer and 500 mb winds exceeds 30 kt or so; this criterion is satisfied rather commonly over the Great Plains in the spring. Note that we have characterized the shape of the hodograph in terms of the behavior of the shear vector with height; the winds themselves almost always veer with height in severe storm environments, but the behavior of the shear vector is more variable. The morphology of the storms that form in a given environment is quite sensitive to the shape of the hodograph of that environment. Thus, care must be exercised in predicting afternoon storm type based on morning hodograph shape; slight changes in the wind structure aloft can have a strong effect on the shape of the hodograph. Nevertheless, when several upper air soundings show a pattern of supercell-type hodographs in a region which is about to experience convection, the forecaster should consider the possibility of tornadic convection in that area. Forecasters can now also use hourly wind profiler data to see if the hodographs are becoming more or less favorable for supercells. The reasons why hodographs with strong unidirectional or veering shear are most likely to produce supercells are still under investigation. The strength of supercell updrafts is accounted for not only by the strong instability usually present, but also by the shear, which carries precipitation downstream and out of the updraft core before it can reduce the buoyancy of the updraft. The persistence of supercell updrafts has been attributed (Lilly, 1986) to their rotational character, which is believed to inhibit small-scale turbulent dissipation. The production of the rotation in supercells is also a subject of recent and current theoretical and numerical investigations. The most prominent current theories all involve the tilting of environmental horizontal vorticity (vertical shear) onto the vertical by an updraft. followed by the concentration of that vertical vorticity by the stretching $\partial w / \partial z$ that occurs within the updraft. However, it is not enough that horizontal vorticity be tilled onto the vertical by a developing updraft; the newly-formed vertical vorticity must be centered within the updraft, and not on its edges. As Davies-Jones (1984) has pointed out, this happens when the environmental horizontal vorticitv has a component narallel to the storm-relative winds (i.e., when the vorticity is "streamwise"). The effects of streamwise vorticity cm a developing updraft can be visualized using the following diagram:

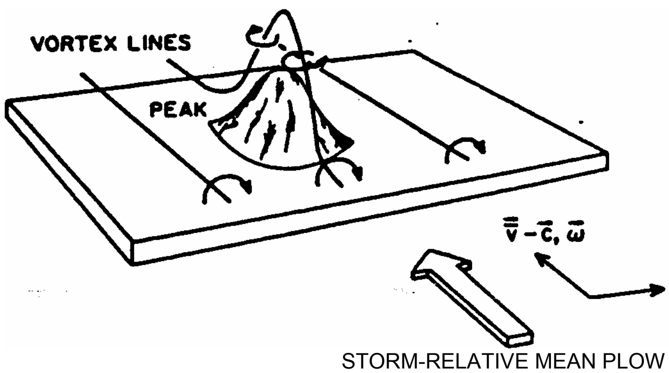


FIG. 8. As in Fig. 7, but for other extreme when vorticity is purely streamwise (i.e., *u* is parallel to v-c). Here. the upslope (downslope) side of the peak is also the cyclonic (anticyclonic) side, and vertical velocity and vertical vorticity are positively correlated.

Here, the hump represents a storm updraft. $\vec{S}$ is the shear vector which is parallel to the hodograph and perpendicular to the horizontal vorticity $\vec{\omega}$. When the storm-relative mean flow $\vec{V}-\vec{C}$, where $\vec{C}$ is the storm motion vector, flows over the updraft, upward motion occurs upstream from the hump and sinking downstream (not shown). The updraft also tilts the horizontal vorticity such that cyclonic vorticity forms on right side (relative to $\vec{S}$) of the updraft. When the flow is streamwise, the cyclonic voracity and the updraft are in the same quadrant (positive correlation) and a rotating updraft (mesocyclone) can develop.

Because the horizontal vorticity associated with the vertical shear always points perpendicular and to the left of the hodograph (recall Fig. 1), the horizontal vorticity of the storm environment is most streamwise when the storm-relative winds point perpendicular to the hodograph. Thus we may say that the streamwise vorticity or "helicity" of a storm's environment is proportional to the dot-product:

$$H = (\vec{V}-\vec{V}_s)\cdot\hat{k}\times\frac{\partial\vec{V}}{\partial z}$$

averaged through the lower troposphere. There are actually three helicity related quantities used in the literature, streamwise vorticity, helicity, and relative helicity with subtle differences between them. In summary, streamwise vorticity $\vec{\omega}_s$ is the helicity normalized by the magnitude of the storm-relative velocity vector, i.e.,

$$\vec{\omega}_s = \frac{H}{|\vec{V} - \vec{V}_s|}$$

One could picture streamwise flow as the toss of a perfectly spiraling football, where its motion and direction of spin share a common orientation.

Relative helicity is a fully normalized quantity (i.e. its value varies between -1.0 and+1.0) and is simply the cosine of the angle between the storm-relative velocity and vorticity vectors, thus

$$RH = \frac{H}{|\vec{V} - \vec{V}_s||\vec{\omega}_s|} = \cos(\theta)$$

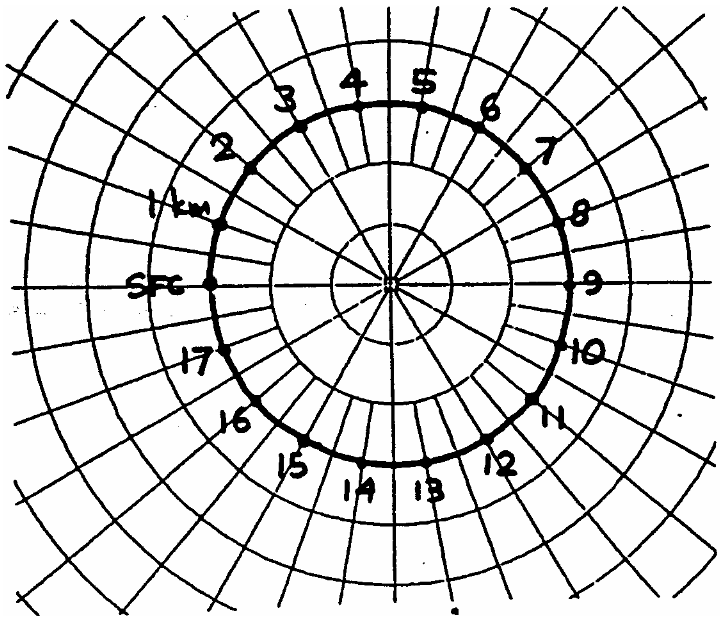
where $\theta = (\vec{V} - \vec{V}_s, \vec{\omega}_s)$, is the angle between the storm-relative wind and the horizontal vordcity vectors respectively.

Why do we look at helicitv?

- Given a particular environment, certain aspects of the ambient flow may enhance the energetics and longevity of storms that develop.
- Hclicity provides yet another method to deduce and/or ascertain information pertaining to the internal dynamics of severe storms.
- Helicity is implicitly coupled to both kinetic energy and enstrophy, consequently, disturbance energy calculations are possible via the "helicity equations".
- Theory suggests the suppression of the inertial energy cascade as a result of the helical nature of a storm.
- From models such as the highly idealized Beltrami flow, which describes a purely helical flow, we can deduce:
    - The rotational characteristics mesocyclone
    - b. The dynamic pressure distribution in and around rotating storms
- Helicity is proportional to the low-level streamwise vorticity, and if taken as a storm-relative quantity is proportional to the strength of the low-level storm inflow.
- Helicity explicitly accounts for storm motion.
- Helicity can be easily calculated from the area on a hodograph diagram.

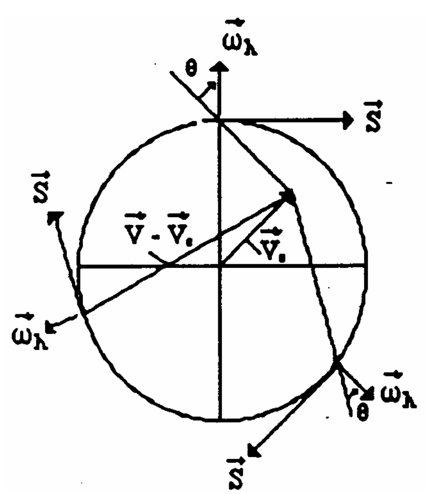
Since a storm can only be considered "steady state" in its own reference frame, it is customary to take H with respect to the 3-D *storm-relative* velocity vector. The total vorticity vector (o is invariant with respect to this transformation.

A simple example of a hodograph which features pure streamwise vorticity at all levels is that of a circular arc hodograph with the storm motion vector located at the center of the circle:

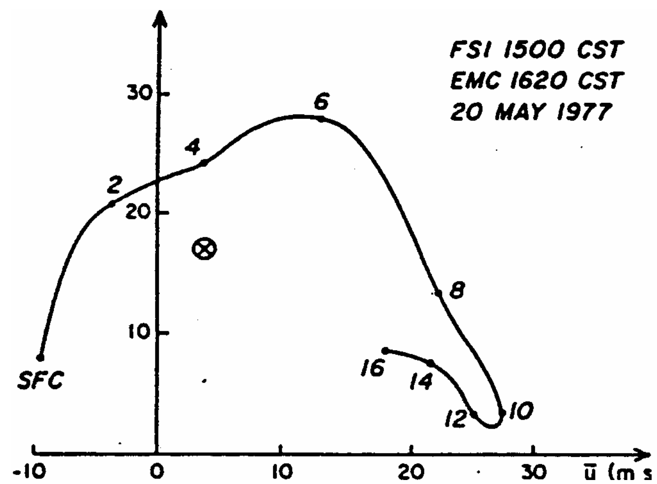


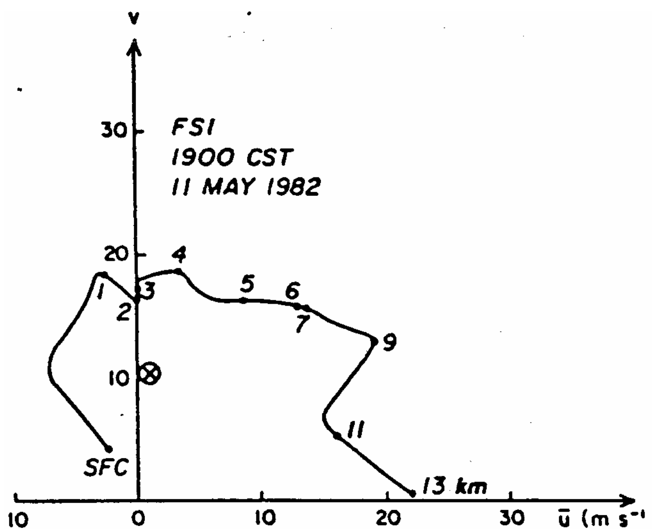
For such a hodograph (a "Beltrami" flow), the vorticity vector ($\vec{\omega}_H$ is everywhere parallel to the velocity vector, and the dot product H defined above achieves a maximum value for the given wind and shear magnitudes.

Therefore, <u>the mean flow has helicity if the shear vector has a component normal to the flow direction.</u> The circular hodograph below shows the relationship between $\vec{\omega}_H$, $S = \partial \vec{V} / \partial z$, and $\vec{V} - \vec{V}_s$. Note that the storm motion is no longer at the center of the hodograph.



Thus whenever an observed hodograph displays vertical shear which veers strongly and smoothly with height, at least through the lower troposphere, and storm motion are expected to lie on the concave side of the hodograph, the development of vertical vorticity within storms should be anticipated. Under such circumstances, supercells might form and these might contain mesocyclones that could produce tornadoes. Examples of hodographs from environments that produced significant tornado outbreaks in Oklahoma are given below.

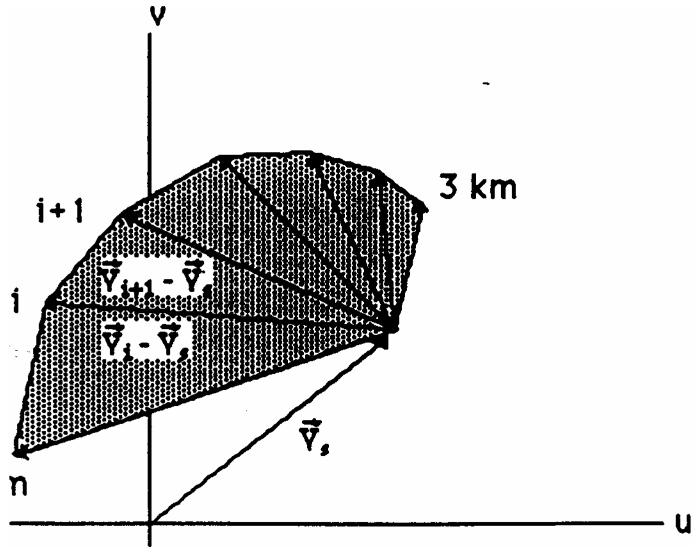




Helicity is an attractive quantity computationally, in that it can be calculated quite simply as an 'area' calculation on a hodograph diagram. Research is currently underway to examine the significant inflow layer depth. Operational applications by Davies-Jones et al. (1990) suggest that 0-3 km is a fairly good indicator of mesocyclone intensity and tornadic activity. As an area under the hodograph, we introduce H,

$$A = -\int_0^z \left[(\vec{V} - \vec{V}_s) \cdot \left(\hat{k} \times \frac{\partial \vec{V}}{\partial z} \right) \right] dz$$

This is just equivalent to minus twice the signed area swept out by the storm-relative winds between the surface and height Z, i.e.



Recall that an area of a triangle with sides a, b, can be represented vectorally as a cross product, $1/2\hat{k}\cdot(\vec{a}\times\vec{b})$, hence if the hodograph is represented by a series of straight line segments then

$$A = \sum_{i=0}^{z} \hat{k}\cdot(\vec{V}_i - \vec{V}_s)\times(\vec{V}_{i+1} - \vec{V}_s)$$

which is twice the area swept out by the two storm-relative wind vectors between i and i+l.

Early results indicate that for tornado producing environments, H ranges from approximately 150 m^2s^{-2} to upwards of 1000 m^2s^{-2}. Davics-Jones (1990) examined the results of 28 tornado cases with the following categories for H:

150 < H < 299	weak tornadoes
300<H<449	strong tornadoes
H>450	violent tornado

It is important to point out that helicity <u>will not</u> determine whether or not storms will develop, but instead indicates how a particular storm (or storms) may evolve given the ambient shear.

Although it might appear at first glance that tornadic storms would be most likely only when the hodograph shows vertical shear that veers strongly with height, such storms are also possible when the hodograph is relatively straight. Considerable streamwise voracity may be present with a straight hodograph if storm motions lie significantly to the right of <u>the</u> <u>hodograph.</u> Such deviant right motion is commonly observed with severe storms, especially isolated supercells. In straight hodograph environments, the effect of vertical shear is to shift the storm's precipitation core onto the downshear side of the storm, where it then tends to suppress and eventually split the updraft

The result is a pair of updrafts which propagate laterally away from the storm motion represented by the "steering level" flow which originally lay on the hodograph. The updraft which moves to the right of the shear vector(right-mover) attains a storm motion which appears slowed to a ground-based observer, it also experiences storm-relative winds which supply it with positive streamwise vorticity, and it therefore begins to rotate cyclonically. The updraft which moves to the left of the shear appears to a ground-based observer to accelerate; it experiences storm-relative winds which supply it with negative streamwise vorticity, and therefore tends to rotate anti-cyclonically.

An example of a hodograph which was approximately straight from 2 km to 11 km of altitude, along with the observed storm motions. (L = left-mover, R = right-mover) for a splitting storm pair, are shown below. Also shown are the tracks of splitting storms observed by radar, and the corresponding tracks of storms simulated numerically for similar environmental conditions.

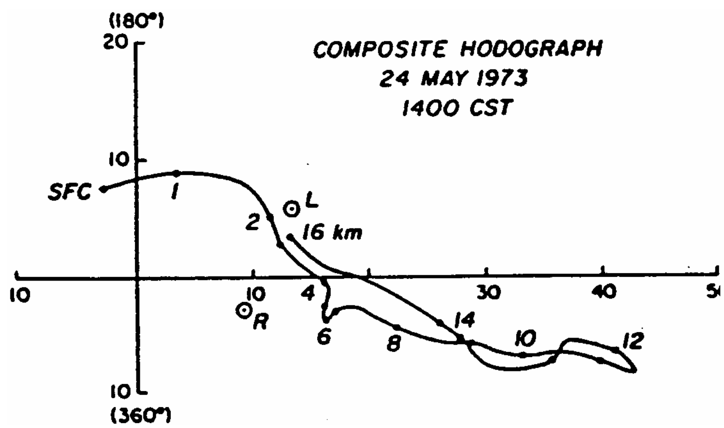


FIG. 11. Proximity hodograph for the Union City, Oklahoma, splitting storm.

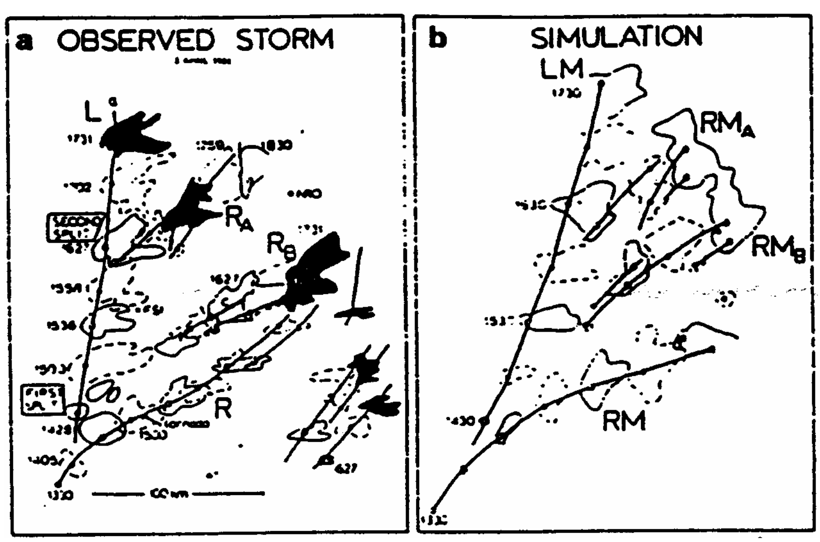


FIG. 18. The observed and modeled storm development on 2 April 1964. The storm are labeled and are several times the contoured regions are stippled for better visualization. (From Wilhelmson and Klemp. 1981.)

The quantitative relations between environmental shear and thermal instability and resulting storm type have been studied with numerical models (Weisman and Klemp, 1982; 1984). The results indicate that a parameter known as the bulk Richardson number (BRN), defined by:

$$BRN = \frac{CAPE}{2S^2}$$

is a good predictor of storm type. In the above formula, CAPE is the convective available potential energy (positive area) of the sounding, and S is $|\vec{V}_{6km} - \vec{V}_{BL}|$, a measure of the low-level storm-relative inflow. According to Weisman and Klemp, storms are likely to be multicell whenever BRN ≥ 45, and may be supercell when BRN ≤ 45. When BRN < 10 with unidirectional shear, storms may be suppressed by the excessive shear, although with curved hodographs this suppression is less noticeable. It should be noted that a shortage of CAPE in a sounding may be overcome if mesoscale or synoptic scale dynamical lifting is sufficiently strong. However, a shortage of shear (equivalent to weak low-level storm inflow) or an unfavorable hodograph shape are much more difficult to compensate for.

In summary, strong vertical shear and a veering or straight hodograph in an environment of veering winds are important in setting the stage for supercell convection and possible tornadoes. Large CAPE is also desirable, although this requirement may be relaxed if strong lifting is present. Absence of shear, however, is an obstacle to supercell development that is more difficult to overcome. Nevertheless, hodograph structure is very sensitive to changes in the wind field, and many mesoscale regions of favorable shear are never sampled by the existing rawinsonde network. This makes it imperative that the forecaster use all available data - surface obs, upper air obs, wind profilers, radar data and satellite images – in assessing the risks of severe weather in the thunder season.

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