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National Severe Storms Laboratory
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On the Source of Thunderstorm Rotation

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U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

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NATIONAL SEVERE STORMS LABORATORY TECHNICAL MEMORANDA

The National Severe Storms Laboratory, Norman, Oklahoma, in cooperation with other government groups, and with units of commerce and education, seeks to increase understanding of severe local storms, to improve methods for detecting these storms and for measuring associated meteorological parameters, and to promote the development and applications of weather radar.

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Generation of vorticity about a vertical axis is considered in light of an order-of-magnitude analysis of the vorticity equation for conditions associated with traveling thunderstorms. Vertical shear of wind in the low-level inflow may act through the tilting term as an important source of vorticity for the storm updraft. The magnitude of this term is estimated in 14 cases from proximity soundings and radar echo tracks, and values obtained agree with the order-of-magnitude analysis. A qualitatively determined correlation between the tilting-term vorticity source and the size of thunderstorm echo is positive in 10 of the 14 cases. A large vorticity source appears to be a necessary but insufficient condition for occurrence of severe weather; severe weather reports were associated with four out of six storms having larger-than-average sources. No clear correlation was found between the sign or magnitude of the tilting-term vorticity source and the deviation of storm motion from the midlevel wind direction. However, for a given variation of vertical shear, the depth of the inflow layer determines the magnitude and sign of the tilting-term vorticity source. More comprehensive observations of the depth and character of the inflow layer are needed to clarify relationships suggested by this study.

1. INTRODUCTION

Evidence that some thunderstorm updrafts have significant rotation about the vertical axis continues to accumulate. The Henderson time-lapse film of a tornado and associated cumulonimbus near Rapid City, S. D., is a remarkably clear example (Koscielski, 1967). A time-lapse film of radar echoes obtained at the National Severe Storms Laboratory on June 10, 1967, shows a tornado-bearing thunderstorm undergoing definite cyclonic rotation. Figure 1 prepared from that film shows the displacement about a central point of peripheral echo features.

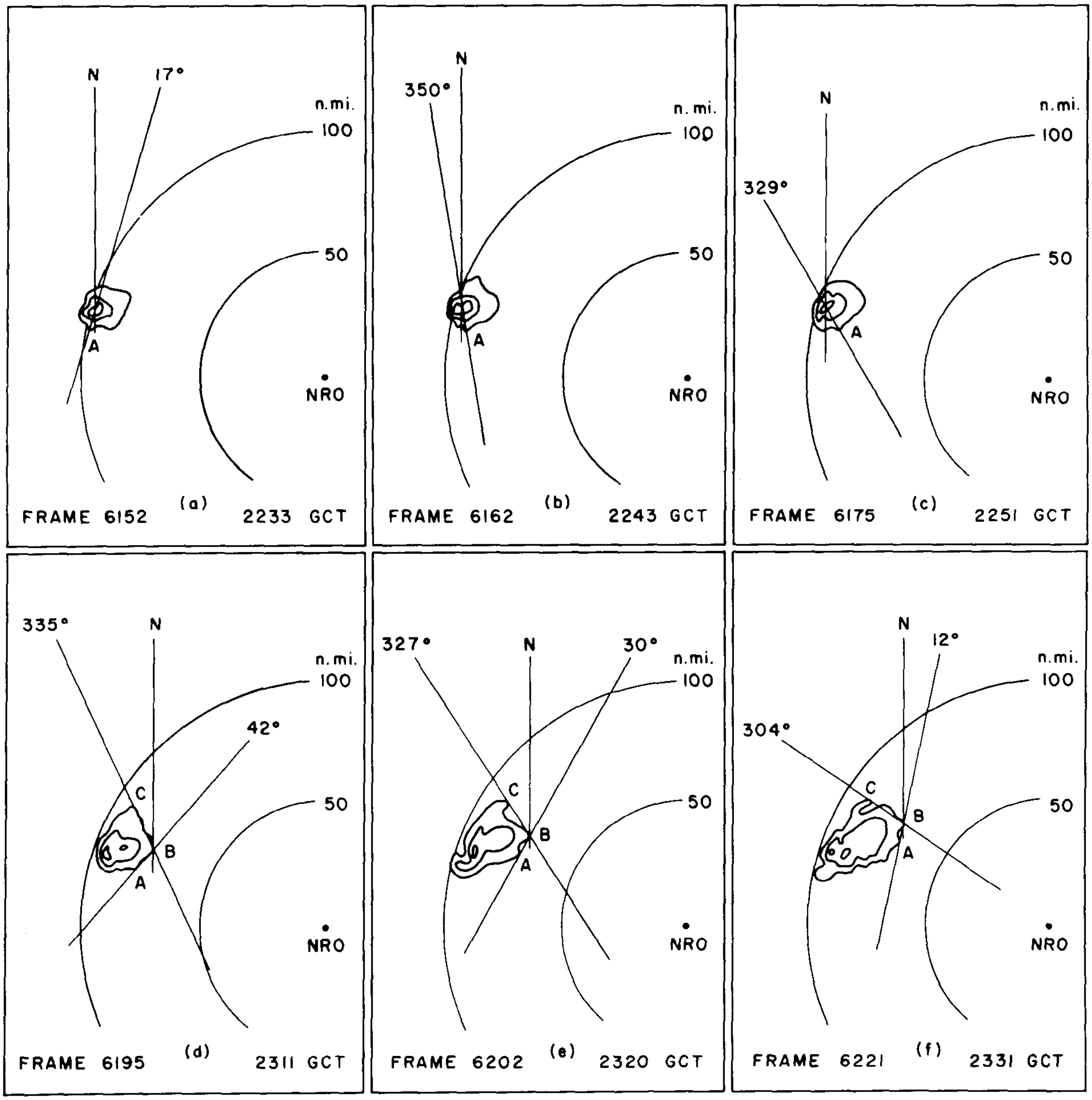


Figure 1. Sequences from time-lapse radar echo film of tornado-bearing thunderstorm, June 10, 1967. In a), b), and c) rotation of line connecting center of maximum reflectivity contour and protuberance A indicates relative vorticity of 7.75×10^{-4} sec^{-1}. In d), e), and f) rotation of cross formed by lines through echo features A, B, and C indicates relative vorticity of 4.50×10^{-4} sec^{-1}.

The source of thunderstorm rotation is still subject to speculation. Fujita and Grandoso (1966) have suggested that an updraft may be induced to rotate if developing in a mid-tropospheric region already undergoing mesoscale rotation. No mechanism has been presented that indicates how mid-tropospheric air enters the updraft in a manner sufficient to produce systematic rotation, although a midlevel "standing eddy" might enhance the rotation of an updraft that has an independent low-level vorticity source.

Conservation of angular momentum in the converging air beneath an updraft has been cited as a likely source of storm rotation (Fankhauser, 1967; Fujita and Grandoso, 1966; Hammond, 1967). Achtemeier (1967) has suggested that a mesoscale low-level jet could produce sufficient horizontal wind shear in the vicinity of thunderstorms to be an important vorticity source. The existence of such a jet has not been demonstrated, however.

There are few data from which the preexistent vorticity field of storm inflow air can be determined. Surface wind fields have been used as an indicator of the sense of rotation aloft, but there is some doubt as to the validity of extrapolating surface fields upward even a short distance. Using instrumented tower data near thunderstorms, Sanders (1967) has shown prominent wind features in the first 500 m above the surface that are not apparent in the surface data. Upper wind soundings have not been obtained in sufficient density, in either time or space, to provide an adequate measure of vorticity on the scale of individual thunderstorms. Aircraft-measured winds circumscribing thunderstorms have been used to estimate ambient vorticity, but there is no basis other than convenience for treating such data synoptically as though the fields sampled were steady-state.

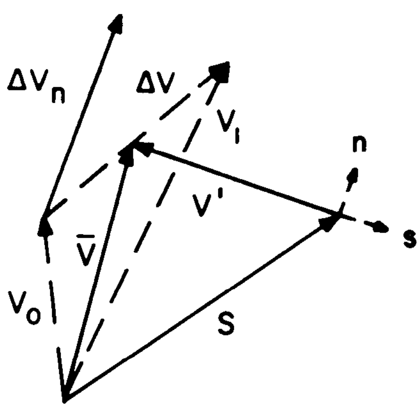
The intent here is not to discount the importance of the convergence term in the vorticity equation, but merely to indicate that few data now available can properly define the existing vertical vorticity component of the inflow to individual thunderstorms -- although it is not beyond the state-of-the-art to obtain such data. In this paper we consider the importance of another source for generating rotation in an updraft, i.e., the frictionally and thermally induced vertical wind shear in the low-level moist air that feeds the storm. We show that the ability of the storm to tap this ever-present source of rotation is a function of the inflow vector relative to the storm and the vertical shear vector in the boundary layer.

2. VORTICITY EQUATION FOR THE UPDRAFT

Consider the vorticity equation for parcels comprising the low-level moist air that enters the updraft of the storm:

$$\frac{d\zeta}{dt} = (f + \zeta)\frac{\partial w}{\partial z} - \frac{\partial w}{\partial s}\frac{\partial v_n}{\partial z} + K\,\nabla^2\,\zeta\,, \tag{1}$$

where ζ is relative vorticity about a vertical axis, f is the Coriolis parameter, w is vertical velocity, v_n is the component of the wind in the n-direction, and K is the eddy exchange coefficient. The direction of s is opposite the inflow vector relative to the storm, and n is normal to the s-axis in the right-hand sense. Figure 2 shows the coordinate system and pertinent vectors. Also, in (1) we have made use of the equation of mass continuity for incompressible flow and have assumed $\partial w/\partial n = 0$ in the vicinity of the storm.



V_o = surface wind

V_1 = wind at top of planetary boundary layer (~ 1 km)

$\overline{V}$ = mean wind in boundary layer

S = storm motion vector

V' = inflow wind relative to storm

ΔV = shear vector through boundary layer

ΔV_n = component of shear vector normal to inflow

Figure 2. Relationship between relative inflow vector and vertical shear vector in boundary layer. Only the component of vertical shear normal to the inflow vector contributes to vorticity generation through the tilting term.

The solenoid term and the term involving the Rossby parameter have been omitted from (1). Because of thermal convection, it is doubtful that any horizontal distribution of solenoids can persist long enough to be an important influence for systematic rotation. In any case, we shall not consider that factor in this paper. Compared with magnitude estimates of the convergence term, the Rossby term is very small for reasonable values of wind speed on the thunderstorm scale.

An estimate of the first two terms of (1) was made by assigning as typical values the distribution of motions shown schematically in figure 3. Table 1 gives the magnitudes of the terms based on figure 3. The estimates indicate that the tilting effect may be an order of magnitude larger than the convergence effect in generating vorticity in an updraft.

However, there is large variation in the magnitudes of both the tilting and convergence terms for reasonable variations in the flow parameters. Table 2 gives an example of this variability. The tilting term may easily vary from 10^{-8} to 10^{-5} sec^{-2}, and the convergence term has nearly the same range of variation.

Table 1. Estimates of the magnitude of source terms in the vorticity equation.

$\Delta v_n/\Delta z$ = 10 m sec^{-1}/km	=	10^{-2} sec^{-1}
$\Delta w/\Delta s$ = -10 m sec^{-1}/30 km	=	-3.3 x 10^{-4} sec^{-1}
$\Delta w/\Delta z$ = 10 m sec^{-1}/4 km	=	2.5 x 10^{-3} sec^{-1}
f = 10^{-4} sec^{-1}		
Tilting term	=	3.3 x 10^{-6} sec^{-2}
Convergence term	=	2.5 x 10^{-7} sec^{-2}

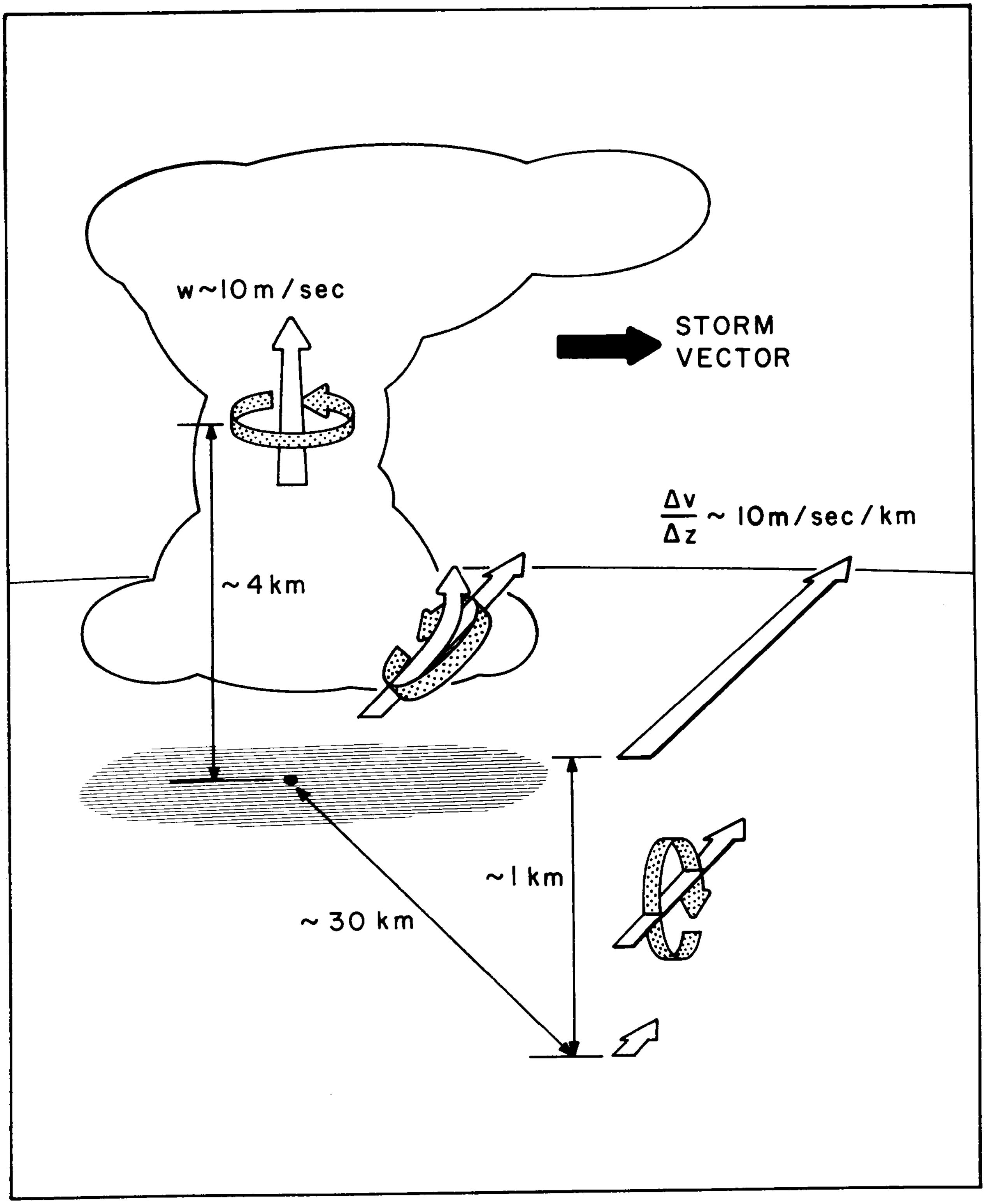


Figure 3. Schematic of process generating vorticity about vertical axis from shear in the boundary layer for a thunderstorm that has a component of motion across the low-level wind field.

Table 2. Range of magnitudes of source terms in the vorticity equation.

$\Delta v_n/\Delta z$	=	1 to 20 m sec^{-1}/km
$\Delta_z w$	=	1 to 15 m sec^{-1}
Δs	=	20 to 40 km
Δz	=	3 to 5 km
Tilting term	=	2.5×10^{-8} sec^{-2} to 1.5×10^{-5} sec^{-2}
Convergence term	=	2.0×10^{-8} sec^{-2} to 5.0×10^{-6} sec^{-2}

To complete the vorticity budget for the storm, the two sources must be weighed against turbulent dissipation, which, for the most part, has unknown variation. The net vorticity generated within any storm depends upon the relative magnitudes and time variation of each of the three effects represented in (1).

In the context of this paper, the sign of the convergence term is determined by the relative vorticity, since there is always convergence in the low-level inflow and f is positive (in the Northern Hemisphere). The sign of the tilting term is governed by the inflow vector relative to the low-level shear vector. For the typical shear vector shown in figure 3, cyclonic rotation is produced if the inflow vector is on the right of the storm's path; anticyclonic rotation is produced if the inflow is from the left. This is not a general rule, because for other shear vector orientations an anticyclonic rotation source can exist on the right flank of a storm, one example of which is shown in section 3. In addition to the usual frictionally induced shear in the boundary layer, thermally induced shear typical of severe storm outbreaks may alter the effect of the tilting term.

The effect of eddy dissipation cannot be quantitatively determined. Its magnitude is probably related to the rate at which ambient air is entrained into the updraft. Entrainment supposedly has less effect on large storms, which would, therefore, stand a better chance of developing significant rotation than would a smaller storm.

3. CASE STUDIES

The importance of the tilting term for vorticity generation was estimated from proximity wind soundings and radar echoes for 16 cases. To be considered, a sounding had to be within a 90° sector centered on the storm's motion vector and also within 30 n mi of the storm. Of the 16 cases, one was eliminated because the sounding began in the cold-air outflow from the thunderstorm. One other sounding was eliminated because it was associated with warm frontal over-running. In these cases, the low-level shears may not have been representative of the shear of the inflow air.

The character of the storm echoes and related pertinent vectors are shown in figure 4. The echo signatures ranged from well-organized squall lines to small but intense cells. The echoes shown were obtained from the NSSL WSR-57 radar operated at zero elevation. All echoes were within 100 n mi of the radar, so the lower portions of the storms are depicted.

Locations of the sounding stations (table 3) are shown by the dots in figure 5. The individual cases were associated with the synoptic-scale conditions shown by the surface and 500-mb charts in figures 6 through 13.

Table 3. List of stations and identifiers.

Upper Air Soundings	
Chickasha, Oklahoma	CHK
Cordell, Oklahoma	COR
Fort Sill, Oklahoma	FSI
Pauls Valley, Oklahoma	PVY
Ringling, Oklahoma	RIN
Wichita Falls, Texas	SPS
Radar	
Norman, Oklahoma	NRO

The tilting effect was estimated by the following procedure:

1) The storm vector, S , was determined by the displacement of the reflectivity maximum over a 30-min period, or in case of more than one such maximum, by the displacement of the maximum nearest the radiosonde station.

2) The mean wind vector, $\overline{V}$, for 1 km above the surface was subtracted trigonometrically from the storm vector to determine the inflow vector, V'.

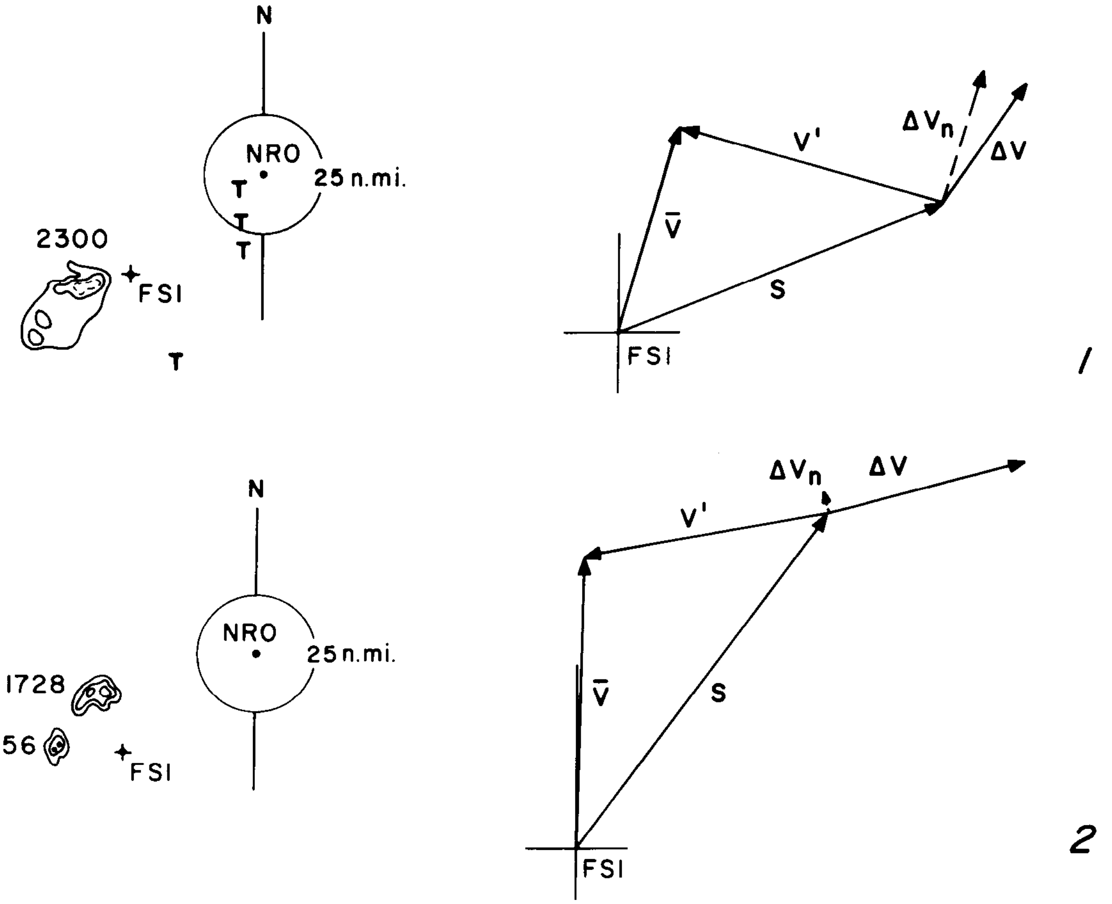


Figure 4. WSR-57 radar echoes and shear vector diagrams. Case numbers are at lower right. Sounding stations are shown by cross and letter identifiers. Greenwich time of echo observation is indicated near echo pattern. Equivalent reflectivity contours are shown for odd powers of ten beginning with $10^{1} mm^{6} m^{-3}$, except for cases 1, 2, and 3, which have contours at 12-dB intervals above the minimum detectable signal. Severe weather reports are indicated by ∇ for hail and T for tornado. Vector descriptions are given in figure 2.

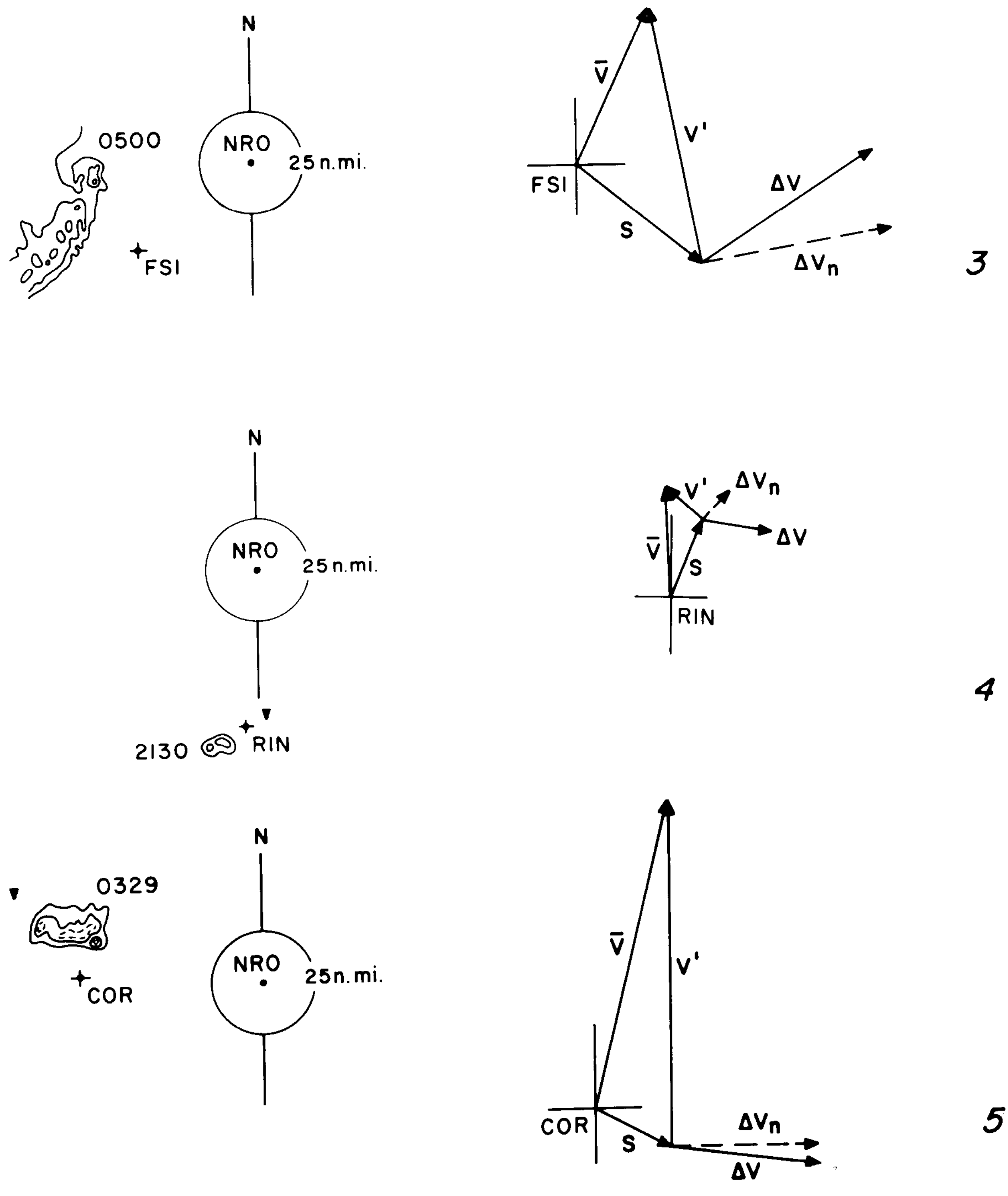
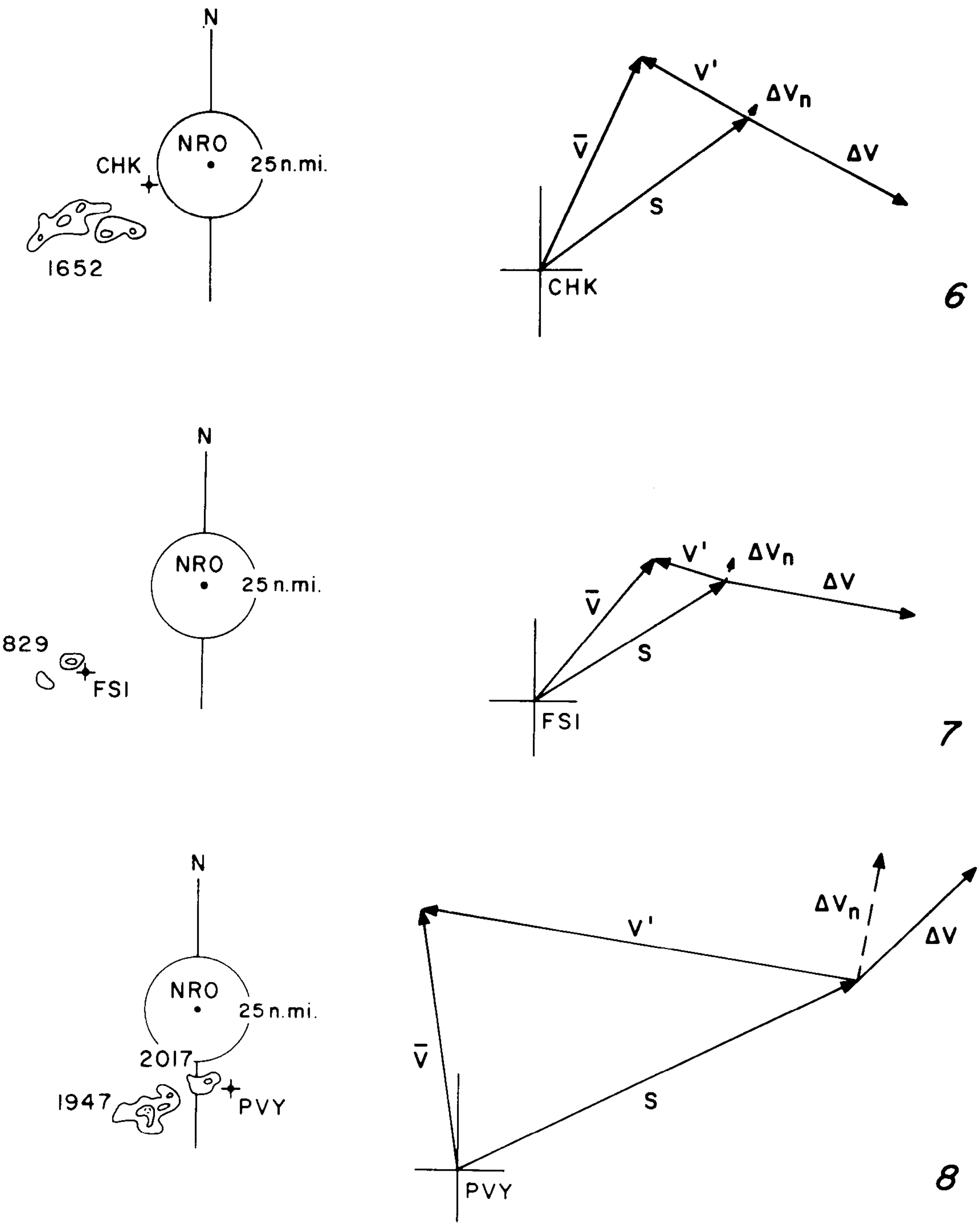


Figure 4 (continued).



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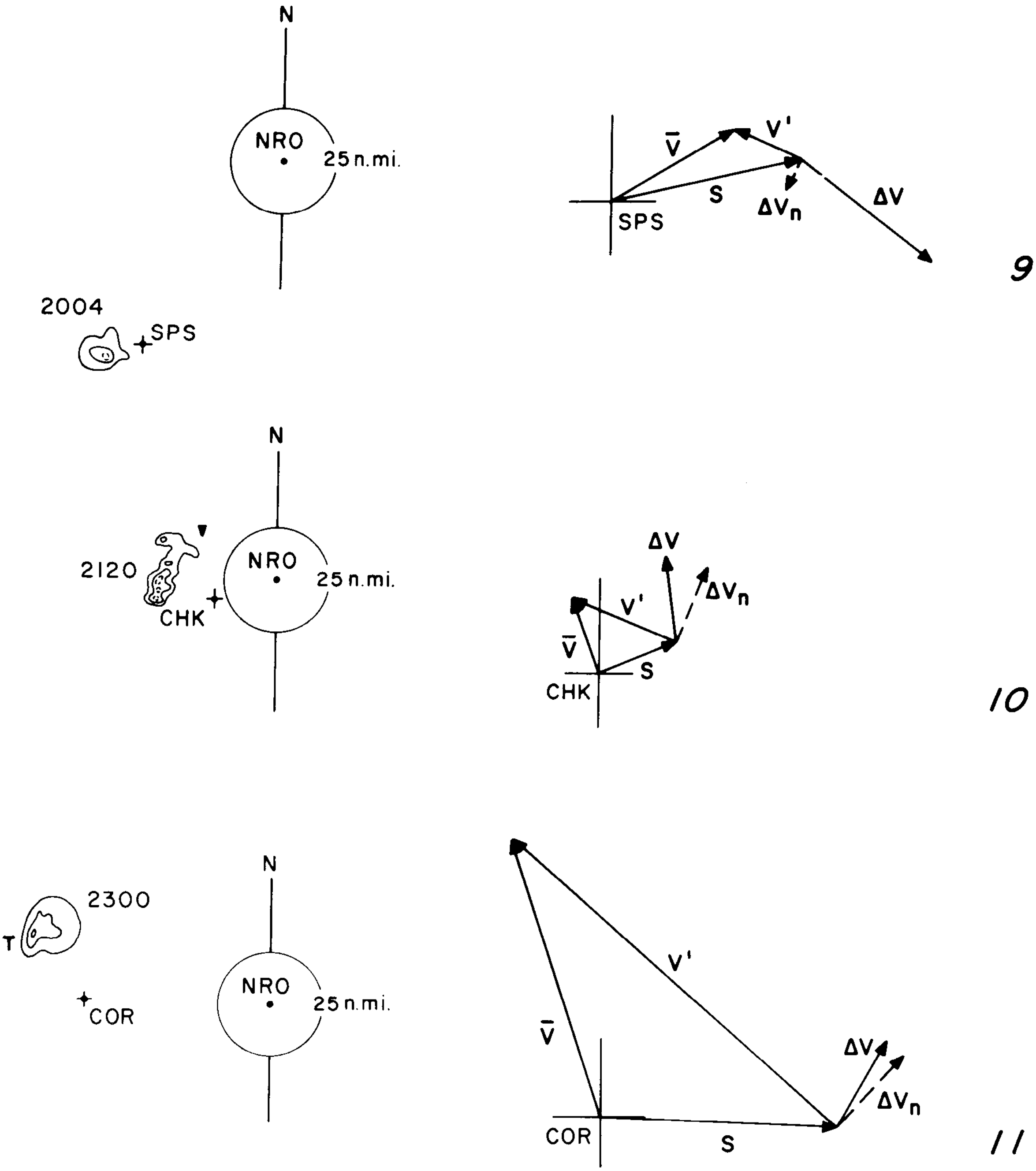

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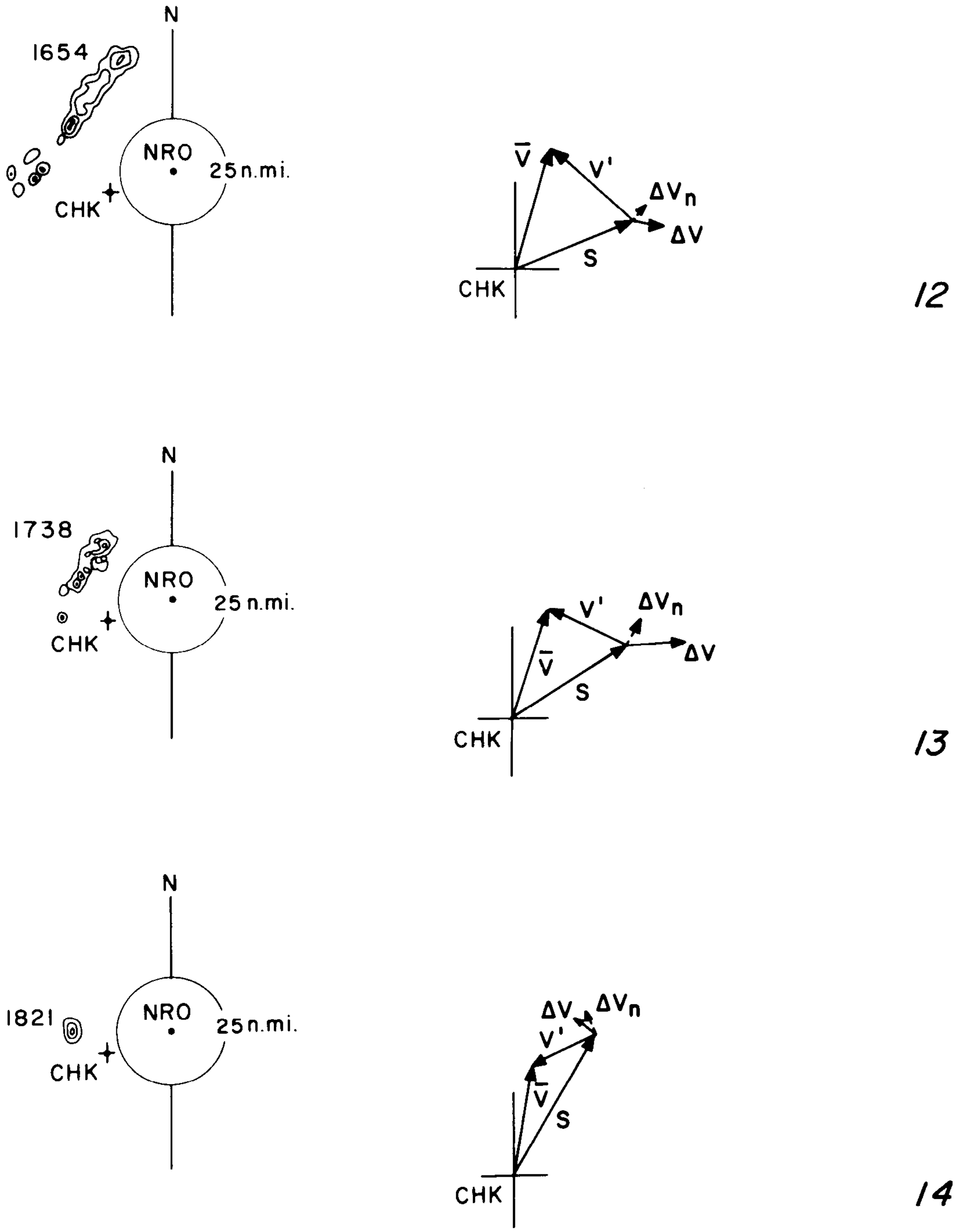

Figure 4 (continued).