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REPORT No. 8

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Radar Observations of a Tornado Thunderstorm in Vertical Section

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U. S. Department of Commerce
Weather Bureau
WASHINGTON, D. C.
APRIL 1962

U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, Secretary
WEATHER BUREAU
F. W. Reichelderfer, Chief

NATIONAL SEVERE STORMS PROJECT

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Radar Observations of a Tornado Thunderstorm in Vertical Section

by

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Bedford, Mass.

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RADAR OBSERVATIONS OF A TORNADO THUNDERSTORM IN VERTICAL SECTION

by

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ABSTRACT

The thunderstorm that produced tornadoes near Geary, Oklahoma on May 4, 1961 was studied by means of a vertically-scanning radar equipped with a two-tone gain switching circuit. The storm configuration was remarkably similar in many respects to the severe hailstorm in England analyzed by Browning and Ludlam. It had an overhang and, at times, a wall and echo-free vault. However, it was not possible to confirm the existence of a period of steady-state conditions in the Geary storm, and it was further complicated by a merger with another storm overtaking it. It also had many precipitation streamers falling through the overhang, which often had cyclonic trajectories.

I. INTRODUCTION

The Geary, Oklahoma tornadoes of May 4, 1961 occurred in a severe thunderstorm situation that was under observation by the combined aircraft, radar, and ground-based meteorological resources of the National Severe Storms Project. In addition, Mr. Neil Ward, of the NSSP staff, and an Oklahoma State Police officer traveled by car to the scene of the activity and made important observations of the tornadoes while they were in progress (Ward, 1961). The present study provides a history of the storm during its growing and active phases as observed by just one of the radars, the Oklahoma City FPS-6, made available by the Air Defense Command, U. S. Air Force. At this preliminary stage of description, no other observations have been included with the exception of Ward's visual reports of tornadoes and a few other reports of tornadoes and large hail that appear to be accurately timed and located. It should be emphasized that the observations presented here are incomplete without further detailed analysis and integration with other available data, and any conclusions must be regarded as tentative at this time.

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[1]Presented at the American Meteorological Society Conference on Severe Storms at Norman, Oklahoma, February 13-15, 1962.

2. RADAR CHARACTERISTICS

The FPS-6 is a vertically scanning radar which displays echoes in a vertical plane and at a controlled azimuth. Its wave length is 10.7 cm., and its peak power is about 4 1/2 megawatts in a pulse of 2 μsec. (providing a resolution in range of 300 meters). The angular beam dimensions between half-power points are 3.2° horizontally and 0.85° vertically. The observations, conducted by U. S. Weather Bureau personnel, were made at a scanning rate of 20 per minute. Consecutive scans were made across the storm and several of its neighbors at azimuth intervals of 2°. Depending on the total azimuth sector that was scanned, the observational cycle varied from just under two minutes to four and one-half minutes, with occasional interruptions of six or seven minutes for reconnaissance of echoes over a wider sector.

The receiver of the FPS-6 radar was modified by a two-tone gain-switching device inspired by a similar circuit developed several years ago at Texas A. and M. College by M. G. H. Ligda and his associates (1958). It was perfected and installed by William Lamkin, of Air Force Cambridge Research Laboratories. On alternate pulses, the device switches the receiver gain from high to low and back to high again. Thus, echoes of high reflectivity, which appear at both high and low gain, are painted on the scope in twice the density of the low-reflectivity echoes which disappear at low gain. For brevity, the higher-reflectivity echoes will be called "core" echoes. Further gain reduction would disclose one or more true cores of still higher reflectivity, within a region referred to herein as a "core" echo.

The two-tone circuit was intended as a qualitative means of displaying echo cores simultaneously with the much larger boundaries of the precipitation echo that would be observed at full gain. The value of reflectivity at the edge of the echo core cannot be specified accurately, since the two-tone circuit was calibrated only infrequently. However, an order of magnitude estimate seems reasonable, based on a calibration taken eight days after these observations. Prior to 1750 CST, the core or high-reflectivity echo was bounded by Z_e (rain-equivalent radar reflectivity factor) of 10^3 mm.^{6}/m.^{3} at a range of 130 n. mi. At a fixed value of receiver gain, threshold Z_e varies with the square of the range so that the boundary is $Z_e = 10^2$ mm.^{6}/m.^{3} at 40 n. mi. After 1750 CST, the low-gain part of the circuit was reduced in gain so that $Z_e = 10^4$ at 73 n. mi. and 10^3 at 23 n. mi.

3. HORIZONTAL ECHO DEVELOPMENT

Radar movies in plan position show the Geary tornado storm first appearing as an echo sometime between 1456 and 1459 CST at the southern end of a line of echoes oriented NE-SW. It was somewhat in advance of the line and about 100 mi. west of Oklahoma City. It moved approximately toward the ENE and later merged with storms forming part of the line behind it. The first accurate tornado report was Ward's observation at 1730 CST.

The FPS-6 radar was first directed toward the storm at 1521 CST. The analysis covers the period 1521-1938 CST. After 1938 CST the storm was difficult to specify because of a combination of deteriorating cell structure, engulfment by other storms, and range of observation too close to record the tops.

Figures 1 and 2 show the boundaries of the core of the storm (low-gain echo) at 30,000-ft. and 45,000-ft. m.s.l. altitude, expressed as the greatest extent in range (fig. 1) and azimuth (fig. 2) as a function of time. (In fig. 2 and subsequent figs., azimuth angles are given with respect to magnetic north and are 9.5° less than the conventional coordinates oriented with respect to geographic north.) If the storm were moving directly toward the radar and maintained a constant radius of ten miles, the two boundaries of figure 2 would be symmetric about the azimuth angle from which the storm was moving, and would cover an increasing angular spread as the storm approached the radar. If the range to the center of the hypothetical storm decreased from 100 to 60 to 20 mi., its angular spread would increase from 11° to 19° to 52°.

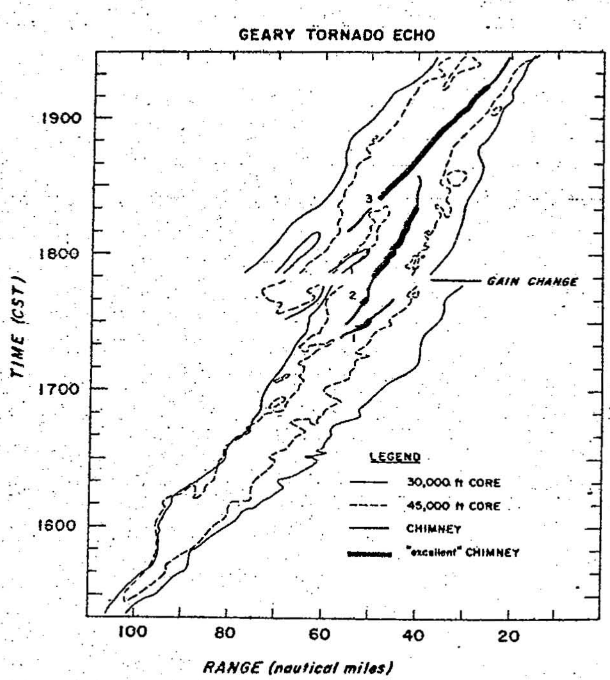

Figure 1. –Range-time tracks of core echo of Geary tornado storm at altitudes of 30,000 ft. and 45,000 ft., with tracks of best chimney locations.

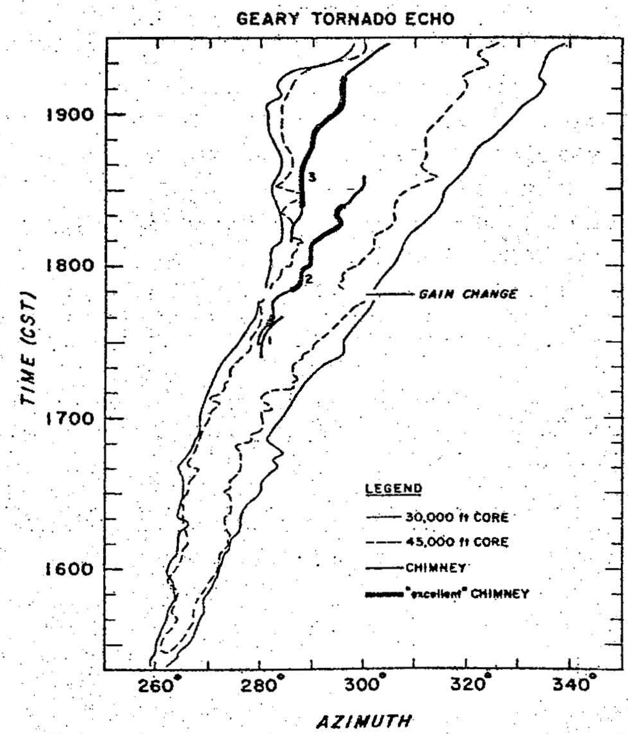

Figure 2. –Azimuth-time tracks of core echo of Geary tornado storm at altitudes of 30,000 ft. and 45,000 ft., with tracks of best chimney locations.

Mergers of the Geary storm with storms behind it are particularly evident at 1802-1810 CST in the 30,000-ft. range-time contour, but are also indicated by the change in slope of the lower azimuth boundary after 1800 CST. Deterioration of the storm near the end of the period is indicated by the narrowing of all contours, and regions of growth at the periphery of the storm are revealed by irregular structures extending outward from the main trend of a boundary, more evident in the 45,000-ft. curves than in the boundary at 30,000 ft. Note, for example, the period 1700-1720 CST. The 45,000-ft. curves are much more irregular than the 30,000-ft. curves, reflecting greater changes in convective activity at the higher altitude. Also, the 45,000-ft. curves are almost everywhere within the limits of the 30,000-ft. curves, showing that the higher tower cores almost always are located directly over an echo core at mid-altitude in the storm. However, the 45,000-ft. boundaries are closer to the 30,000-ft. boundaries for lower azimuths and greater ranges, indicating an asymmetric configuration of the towers with respect to the 30,000-ft. core: the towers tend toward a location above the southern and western sectors of the 30,000-ft. echo.

The tracks of "chimneys" are also plotted on figures 1 and 2, but this feature will be discussed later.

4. VERTICAL ECHO DEVELOPMENT

Figure 3 shows the rise and fall of major tower tops.[2] During the period 1521-1850 CST a total of 36 towers was identifiable, but only 14 of these exceeded all other tops at one time or another and are plotted on the diagram. After camera trouble at 1850 CST, the first sequence of pictures was taken at 1903 CST, and no relationship could be found between the towers before and after this data gap. Also, the 4-min. cycle after 1903 CST was too long for positive identification of towers from one sequence to the next, partly because of instability in the storm and partly because large azimuth changes taking place over the short range were confusing to the analyst. Therefore, from 1903-1938 CST only the highest towers at each observing time are plotted, as little dots.

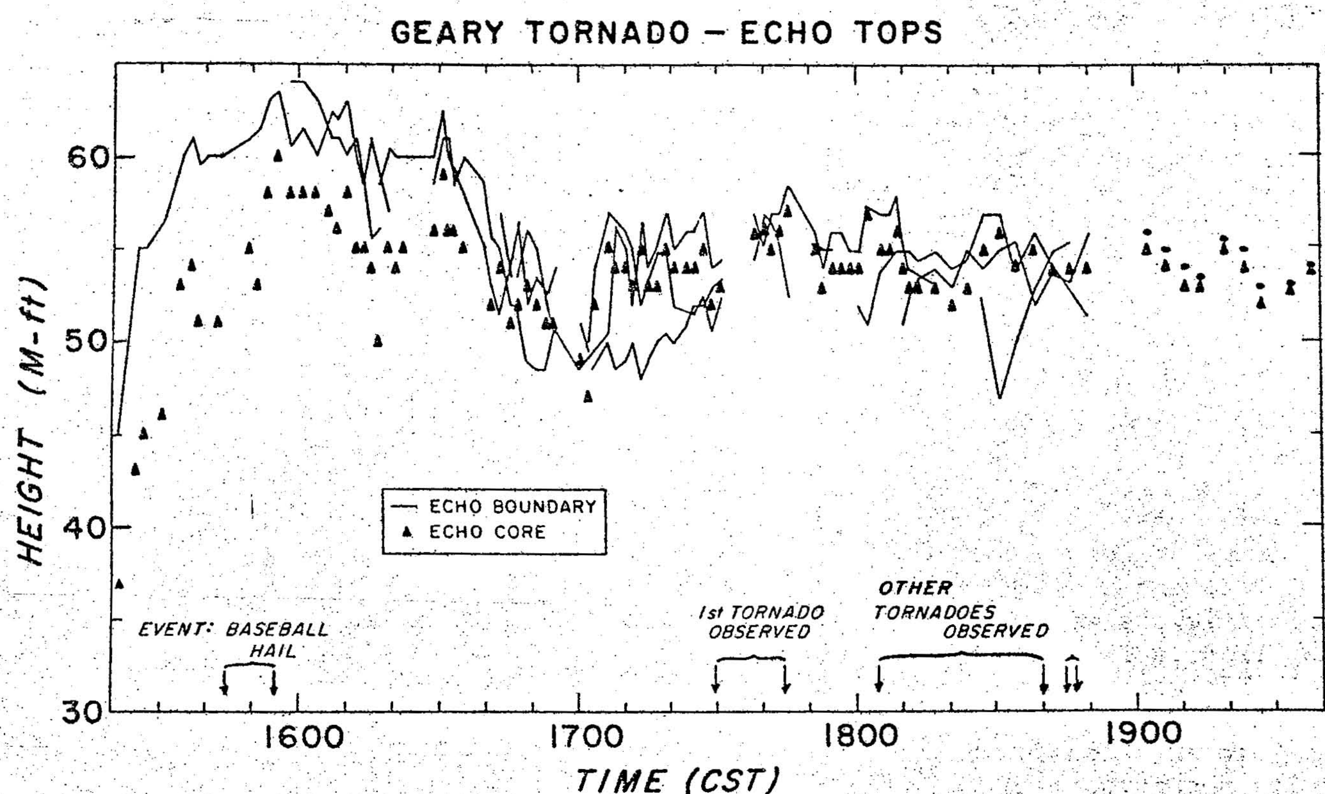

Figure 3. –Development in time of echo tops of individual towers of Geary tornado storm. Little triangles denote tops of the high reflectivity echo core.

[2]The towers observable in this storm have much longer lifetimes and larger sizes than visual cloud turrets at the top of a cumulonimbus. It is difficult to identify small-scale, short-lived cloud turrets with radar because of the poor angular resolution of the radar beam compared with optical methods of measurement. In the case of this particular radar observation, the difficulty was compounded by the inability to separate echoes of maximum reflectivity from surrounding echoes of moderately high reflectivity.

The little triangles on figure 3 denote the tops of the core, or low-gain echoes. (The lines are the highest high-gain, or low-reflectivity echo.) In every case the highest core echo occurred in the tower having the highest top at high gain. Note the diminishing spread between core top and echo top with time. During the early stage of the storm (up to the maximum in the first tower at 1555 CST) this diminishing spread very likely indicates development of the storm as its core intensified, rose, and covered a larger area. Another contributing cause is related to the height resolution of the radar beam. When the first top was measured, its range from the radar was 104 n. mi., but after 1930 CST the highest tops were within 20 mi. The radar undoubtedly overestimates the tops by at least one-half the vertical beam width, or 0.4°, which amounts roughly to 1000 ft. for each 20 mi. of range. Depending on the structure of the echo top, the overestimation may be even twice this amount. As a rough approximation, the indicated core top may give a more valid idea of the true echo top; thus, the storm probably never exceeded 60,000 ft. in height and after 1640 CST spent most of its time in the 50,000-to 55,000-ft. range.

Except during the early build-up period, the vertical movements of towers were extremely complex. Sometimes several towers fell or rose together, but sometimes ascending and descending motions were taking place simultaneously. Up to 1850 CST the towers could be identified with ease between 2-min. periods and usually without much difficulty between 4-min. cycles. Whenever a data gap of six or seven minutes occurred, however, there was almost always serious trouble in carrying through the identification of towers. Even though the fine structure of the towers was not visible with the relatively low value of Z_e at the core echo boundary, the time between successive observations of a tower should be no more than 5 min. to assure reliable identification of the tower.

In the Geary storm there were two periods of general echo top build-up separated by a period of echo top descent. The severe weather also followed this pattern, with some time lag. The early echo top rise period (1521-1555 CST) was followed first by heavy hail, reported up to the size of baseballs, that began to cover the ground at about 1545 CST, then followed by at least another occurrence of large hail and one or more funnel clouds aloft. (Events for which there is not confidence in timing accuracy are not listed on fig. 3.) Echo tops descended significantly from 1630 to 1702 CST, and the best deduction that can be made from the cooperative observer data indicates a complete lull in severe weather from about 1645 to 1730 CST. The rapid echo top rises from 1700 to 1708 CST (culminating in more gradual ascent to a new top at 1745 CST) were followed by tornadoes and several reports of one-inch hail in the period 1730-1845 CST. This sequence of two periods of violent behavior and high echo tops, with the violent weather lagging echo top rises, is similar to the performance of a tornado-producing hailstorm of June 1, 1956 in New England (Donaldson, 1958).

The maximum ascent rates of the towers of the Geary storm (fig. 4) also show two pronounced periods of peak activity, one at the very beginning, and several towers ascending at rates in excess of 10 m./sec. during 1650 to 1716 CST. The greatest ascent rate of 17.5 m./sec. was observed between 1706 and 1708 CST. After 1815 CST the cycling period of observations was three and one-half to four minutes, so possibly the ascent rate of 9 m./sec. at 1830 CST might have indicated a considerably greater rate if observed over a 2-min. period.

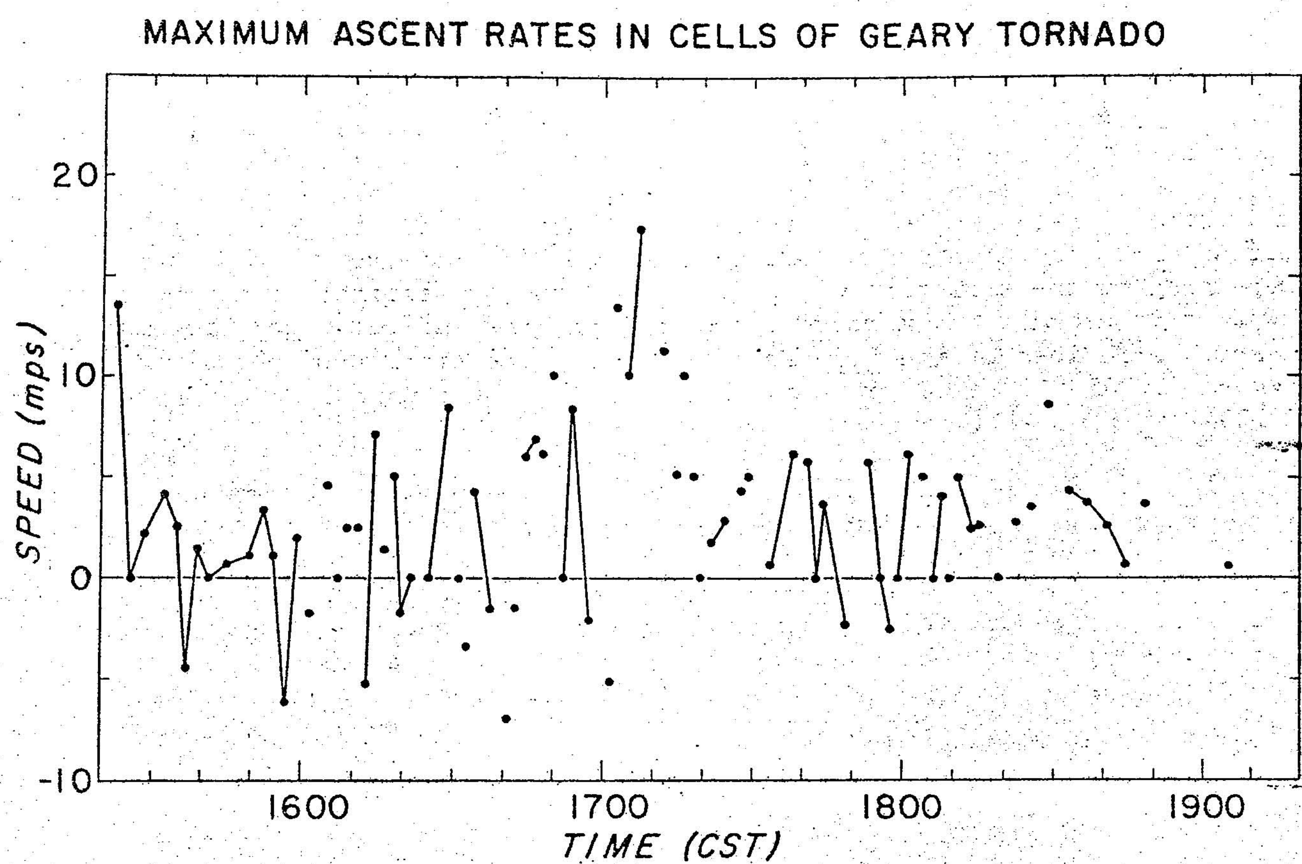

Figure 4. —History of maximum observed ascent rate of echo towers. The lines join consecutive values in the same tower.

On figure 4, a straight line connects points where the same tower exceeded all others in ascent rate on consecutive observations. Up to 1600 CST there was virtually no competition, since one tower dominated the storm up to that time. After 1600 CST, however, the maximum ascent rate shifts 45 times from one to another of 19 towers. Five of the towers had two or more periods during which they ascended at a rate of 5 m./sec. or greater, separated by periods of top descent. One might, therefore, characterize the top of the storm after 1600 CST as very active and complex.

Nine of the towers could be tracked for 20 min. or longer. In fact, the first tower was in view for nearly an hour. The trajectories in plan view of these persistent tower tops are plotted in figure 5, together with areas where the ascent rate of highest echo tops or echo core tops exceeded 10 m./sec. Of special interest here is the cluster of rapid ascent rates just west of the tornado area. Two of these are in towers whose tracks are not shown because of their short lifetime. Another interesting point is the oscillation in the track of tower (s). Also note tower (β) which moved in a direction about 40° to the right of the other towers and intersected two of their trajectories after they had passed. This tower originated 3 min. after merger of the original storm core with the core of an echo overtaking it from the west. Tower (β) maintained the direction of the overtaking echo.

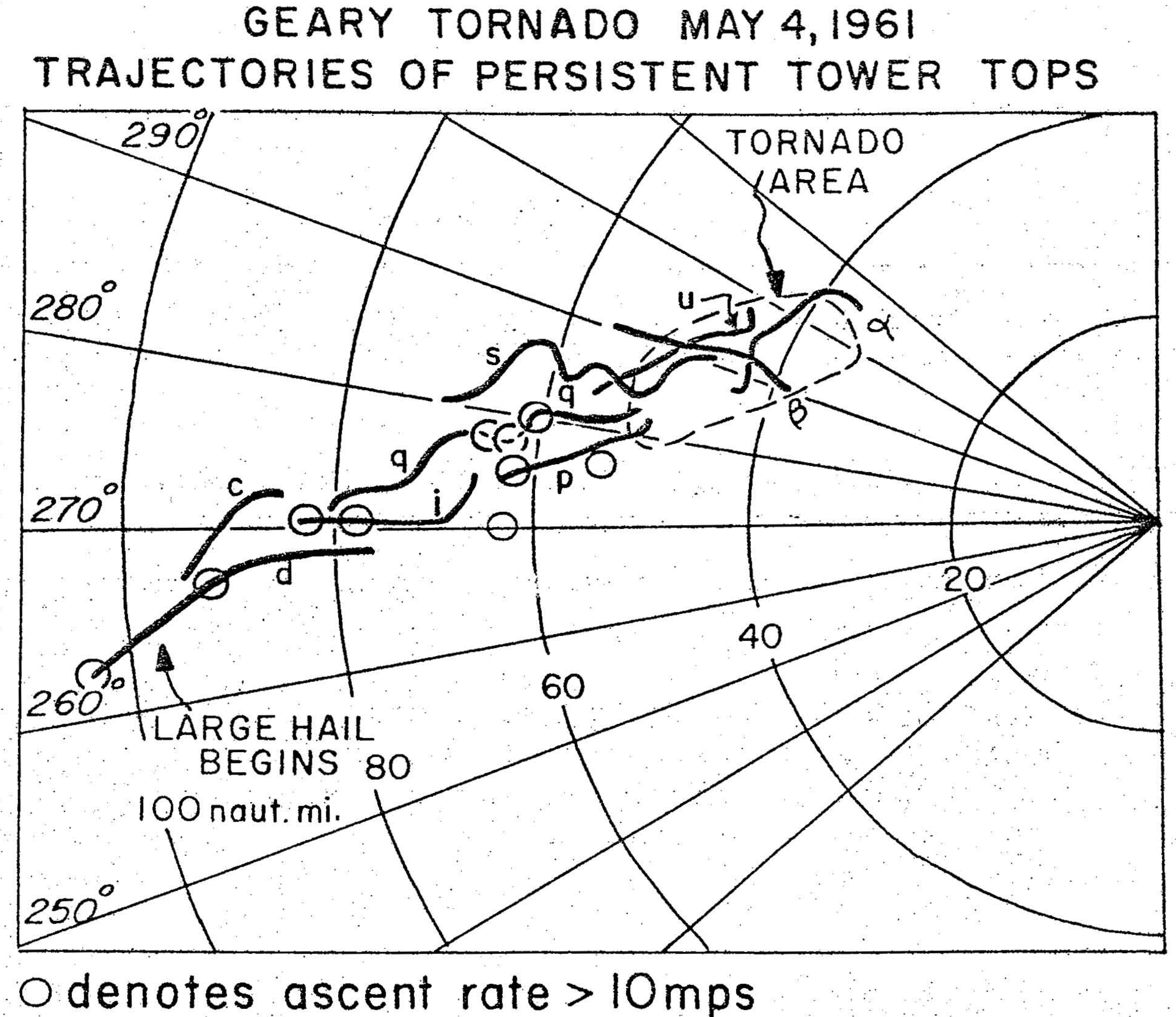

Figure 5. –Trajectories of echo tower tops persisting for twenty minutes or more. The radar is at the origin of the polar coordinates.

5. THE OVERHANG

A severe hailstorm over southern England on July 9, 1959 was studied by Atlas and Ludlam (1961) using three radar wavelengths; by comparing reflectivities at the different wavelengths they were able to deduce hailstone sizes and concentrations. Using these results and other data gathered during the day, Browning and Ludlam (1960, 1962) examined the storm in great detail and derived a self-consistent model of the air flow in and about the storm. One of the remarkable features that they discovered was the "overhang," or echo at 12,000 ft. and higher, overriding a lower region with no echo. They demonstrated how the overhang region indicates the presence of inflowing, rising air beneath it.

The Geary storm was also notable for its overhang; this feature persisted throughout most of the duration of the storm. The first suggestion of an overhang appeared at 1527 CST, when some areas of less than core intensity appeared under a small part of the core at 30,000-ft. altitude. The first really good overhang showed up at 1551 CST when in the southern (right flank) part of the storm the core extended downwards only to 19,000 ft. with the exception of a smaller streamer descending to 12,000 ft. However, at this time the area under the overhang was filled with low-reflectivity echo.

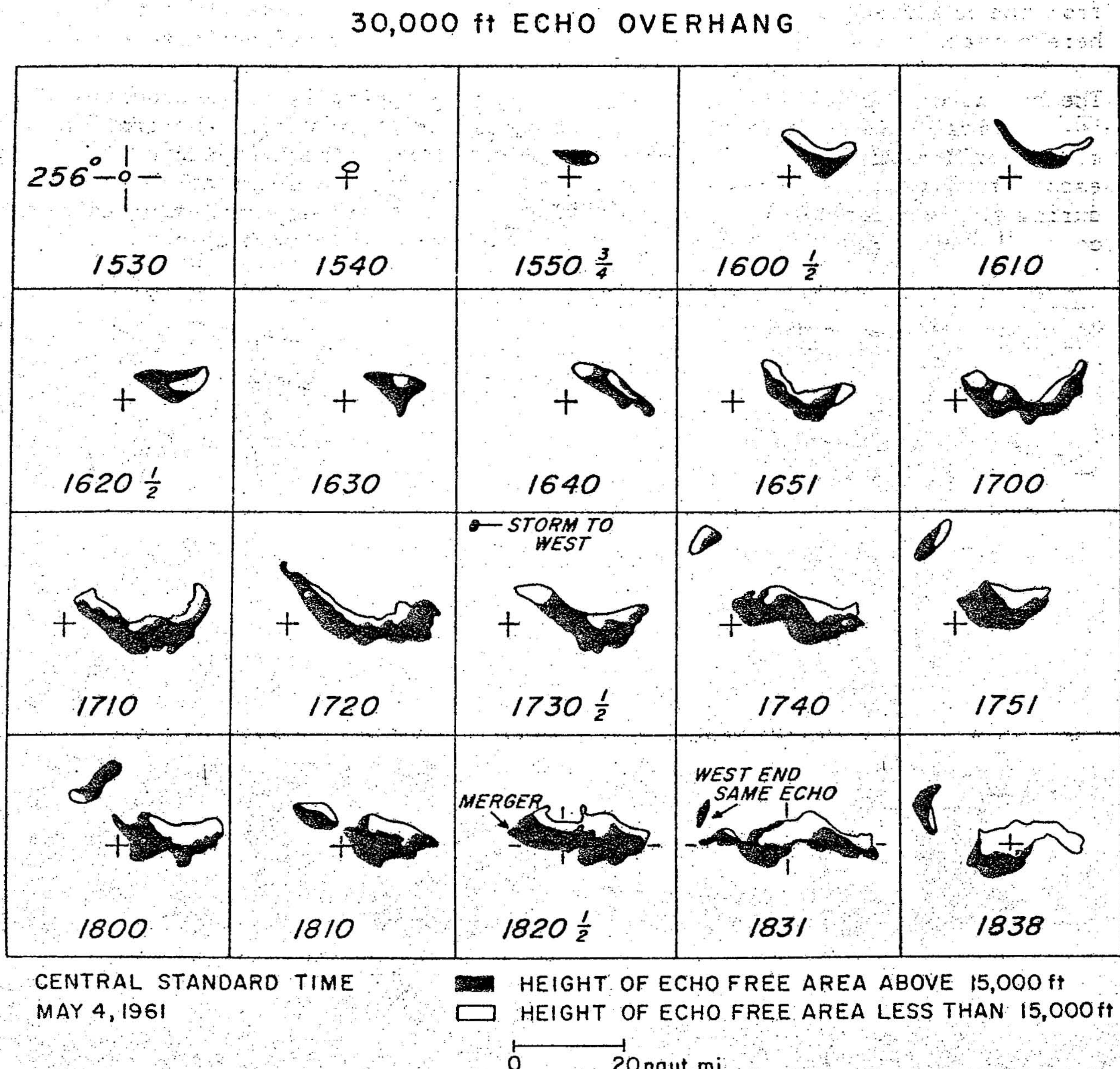

Figure 6. –Development of overhang, or that portion of the 30,000-ft. core echo lying above a region with no echo or low-reflectivity echo. Direction of travel is to right, and crosses denote a mean-velocity position at each time. The portion of the storm having echo at low elevations is not shown. The large overhang area at 1800 CST corresponds to the unstippled area in the plan view in figure 14, where the relation to low-level echo may be seen. The smaller overhang to northwest is part of a separate storm, about to merge.

The first sizable echo-free region appeared under the core overhang at 1628 CST. Up to this time the overhang might be interpreted as a tilting of the core toward the right flank of the storm; but from 1630 CST onward parts of the overhang were higher toward the center of the storm than on its right flank, and there was no doubt of the existence of strong forces in the overhang region preventing the fallout of a considerable portion of the core echo above it.

Tracings of the extent of the overhang in plan position, synthesized from the RHI photographs, are reproduced in figure 6. No distinction is made here between echo-free space and space filled with low-reflectivity echo; both are considered "overhung" if core echo at 30,000 ft. lies above them. The height of the echo-free or low reflectivity region is coded according to its vertical extent above or below an altitude of 15,000 ft. The crosses give an indication of the departure of the center of the overhang area at each time from a constant average velocity of 23 kt. in a direction from 242° during the indicated time interval. (This velocity is somewhat misleading because the overhang in its later stages is effectively slowed down by the merger of the original storm with its western partner which also featured an overhang from 1730 CST onward.) The overhang continued for about an hour beyond the last tracing of figure 6.

The overhang was located in the forward and right sectors of the 30,000-ft. core echo, and increased in relative size up to 1800 CST when it covered about one-half of the total core area at 30,000 ft. The proportion of 30,000-ft. core area included in the overhang gradually diminished after 1800 CST.

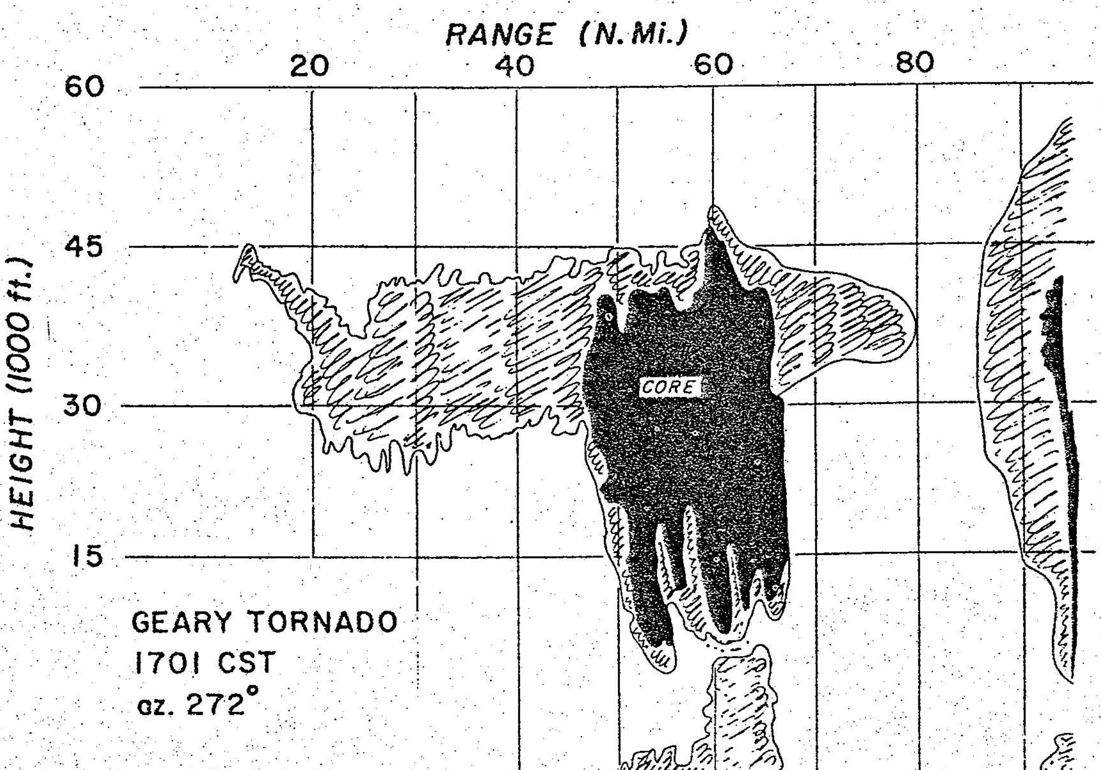

Figure 7. –Tracing of Geary storm echo in vertical section at 1701 CST, showing streamers falling beneath the overhang. High-reflectivity (or core) echo is shown in black. Storm is moving to left.

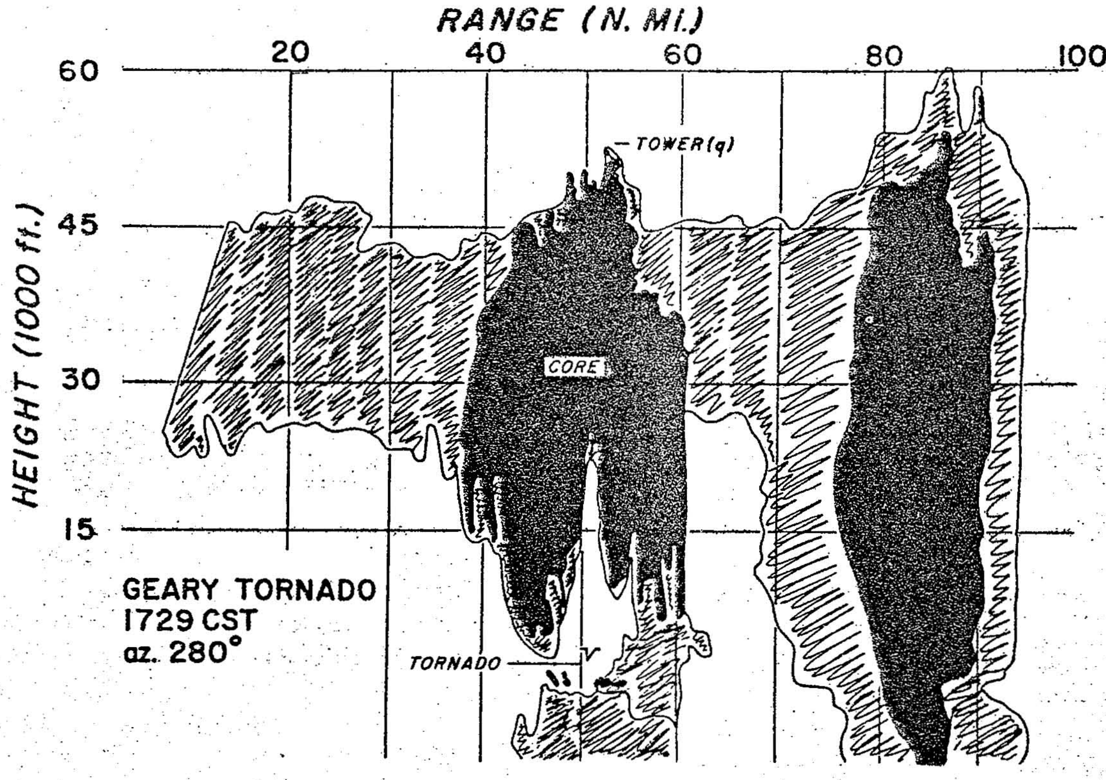

Figure 8. —Tracing of Geary storm echo in vertical section at 1729 CST, at approximately the time and location of the first tornado observed by Ward.

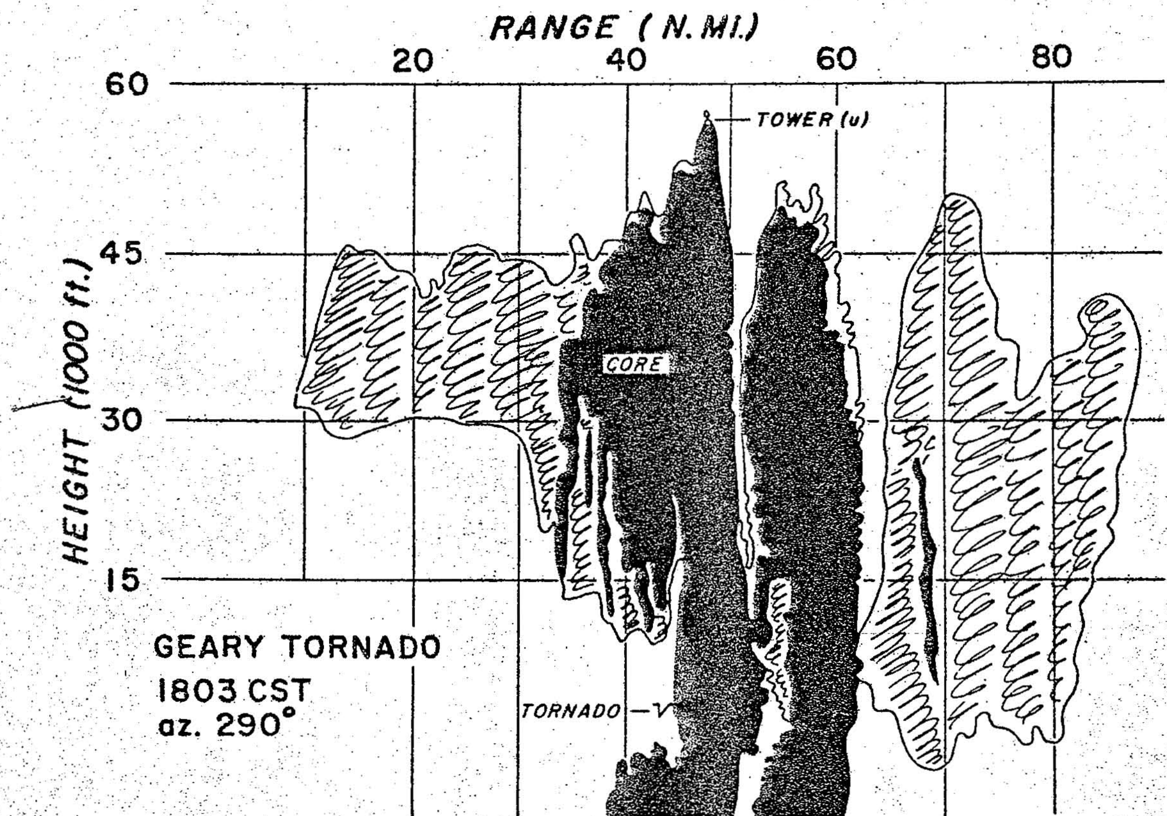

Figure 9. —Tracing of Geary storm echo in vertical section at 1803 CST, just before another tornado sighting by Ward. Wall echo is to the rear of the tornado symbol, and chimney extends above it. Echo behind main storm is about to merge with it.

Figures 7, 8, and 9 show sections through the overhang at three interesting times, spaced about a half hour apart. Note the streamers of echo penetrating the overhang, like giant mammata. Conventional mammata, observed by Ward on his way out to meet the tornadoes, are indicated on figure 7 by the protuberances below the anvil between 20 and 33 mi. range. Figure 7 has another interesting feature, the small loop of echo near the ground that seems to join two of the streamers.

Figure 8 shows the echo configuration at the time and place of the first tornado noticed by Ward. Above the tornado there is a large space extending upward, free of echo to 23,000 ft. and not filled with core echo for a further 2500 ft. Browning and Ludlam noted this characteristic of their severe hailstorm. They called it the "echo-free vault" and I denote it "chimney" for convenience and for generality to extend the definition to include areas of low-reflectivity echo penetrating upward into the core.

Figure 9 shows an echo section very near the time and place of another of Ward's tornado sightings. At this time the "wall", described thoroughly by Browning and Ludlam, is present a short distance behind the tornado. (The direction of storm movement in figures 7, 8, and 9 is to the left.) Here the chimney is a bit lower: it extends echo-free to 18,000 ft. and can be traced through low-reflectivity echo to 22,000 ft. The merger of the main storm with its neighbor to the west is just beginning.

6. CHIMNEY HISTORY

Three chimneys, the latter two well formed, occurred in the Geary storm. Detailed tracks with time of the movement of the highest part of each chimney are plotted on figures 1 and 2, and trajectories of the paths swept out by the total indicated extent of the chimneys are sketched on figure 10. Tornado locations reported in detail in a private communication by Ward are also spotted on figure 10. All of Ward's tornadoes seem to be associated in some way with chimneys 1 and 2, with the exception of two small, brief vortices observed around 1845 CST for which no association could be found.

Bigler (1958) showed the association of a Texas tornado with an echo-free hole in a thunderstorm echo, and mentioned other observations of this association. These echo holes might have been unrecognized chimneys.

It is interesting to examine how the chimneys were formed. Chimney 1 never had a wall and lasted 17 min. at most; it was well formed for only 4 min. In these two respects it was radically different in character from the other two chimneys. Its configuration very likely was caused by nothing more than an incidental space between echoes. Hence the name "chimney", which implies an updraft, is misleading as a designation for a space between echoes which might have been a region of downward motion.

The space called chimney 1 occurred between the main echo and new growth on its western, or rear side. The new growth was first visible at 1717 CST about 2 mi. to the west of the Geary storm. It developed explosively: 2 min. after detection it had a core from 15,000 to 25,000 ft.; in another 2 min. the core extended upward to 36,000 ft. and was beginning to merge with

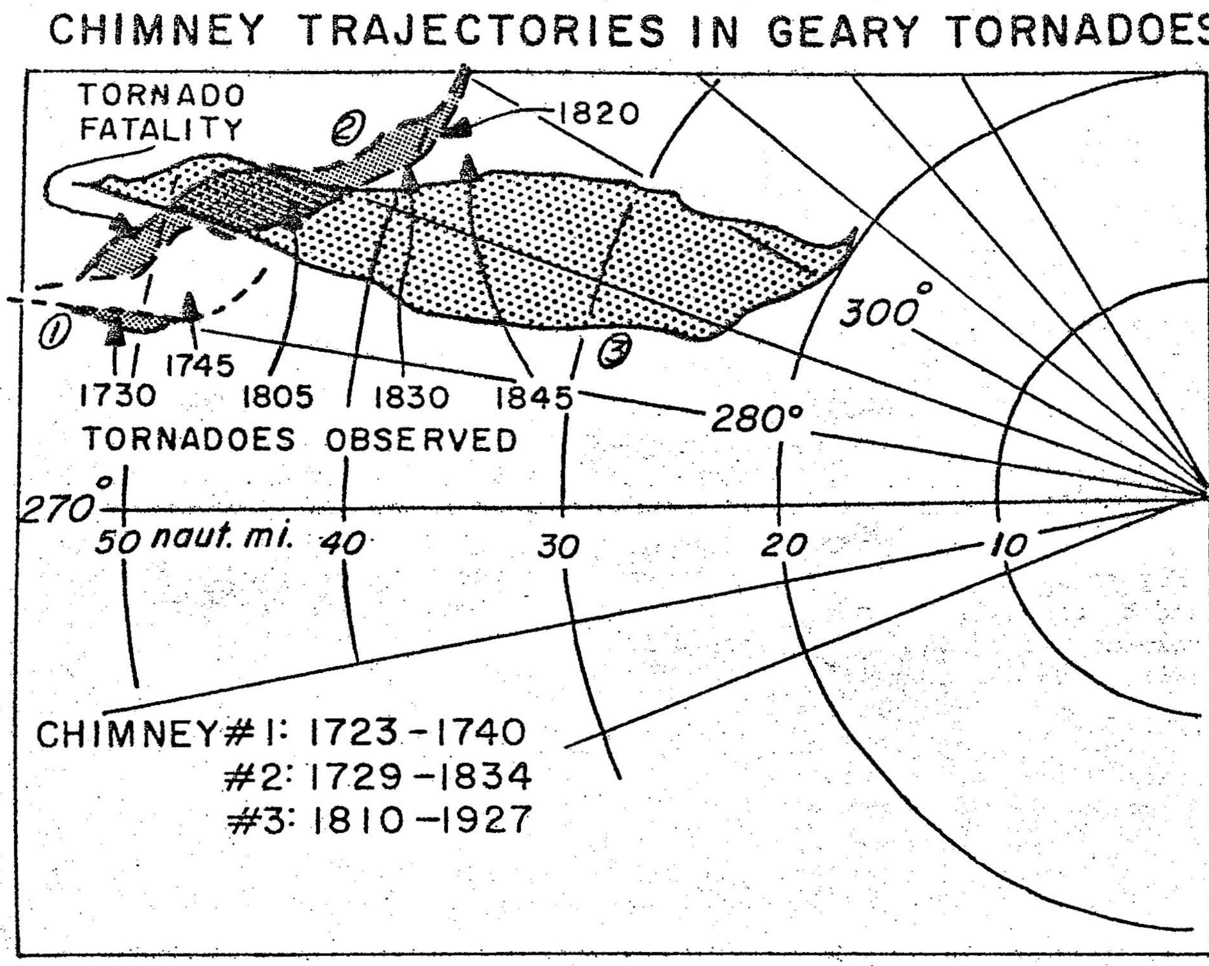

Figure 10. —Areas swept out by chimney-wall echo configurations in Geary tornado storm. The areas include the total extent of chimneys and their associated walls without regard to quality or height. The best-defined chimney shapes, as in figure 9, are located roughly in the center of the dotted areas.

the main echo. At 1727 CST, 10 min. after first detection, the new growth had grown in area to about the same size as the main echo at altitudes of 20,000 ft. and lower, and was solidly merged at higher altitudes. Chimney 1 was first judged to be "good" at this time. At 1738 CST, after a frustrating data gap, chimney 1 was poor, very wide, and definitely dissimilar in shape to any kind of a smokestack. It was more like an inverted bowl among the streamers.

Chimney 2 first formed in the explosive new growth at 1729 CST, about 5 mi. west of chimney 1. Its height was 14,000 ft. at this time and it had a wall even at the beginning. At 1740 CST it extended up to 20,000 ft. and was judged "good" in appearance. During the next 10 min. it deteriorated somewhat, but at 1751 CST it became "excellent" and stayed in good shape through 1820 CST. Then it deteriorated fairly rapidly. It reached its maximum height at 1756:30 CST of 24,000 ft. echo-free and 26,000 ft. low-reflectivity echo (fig. 11). At this time its lateral extent normal to the storm direction was also maximum, estimated to be 4 mi. Its average echo-free height was 15,000 ft. during its lifetime.

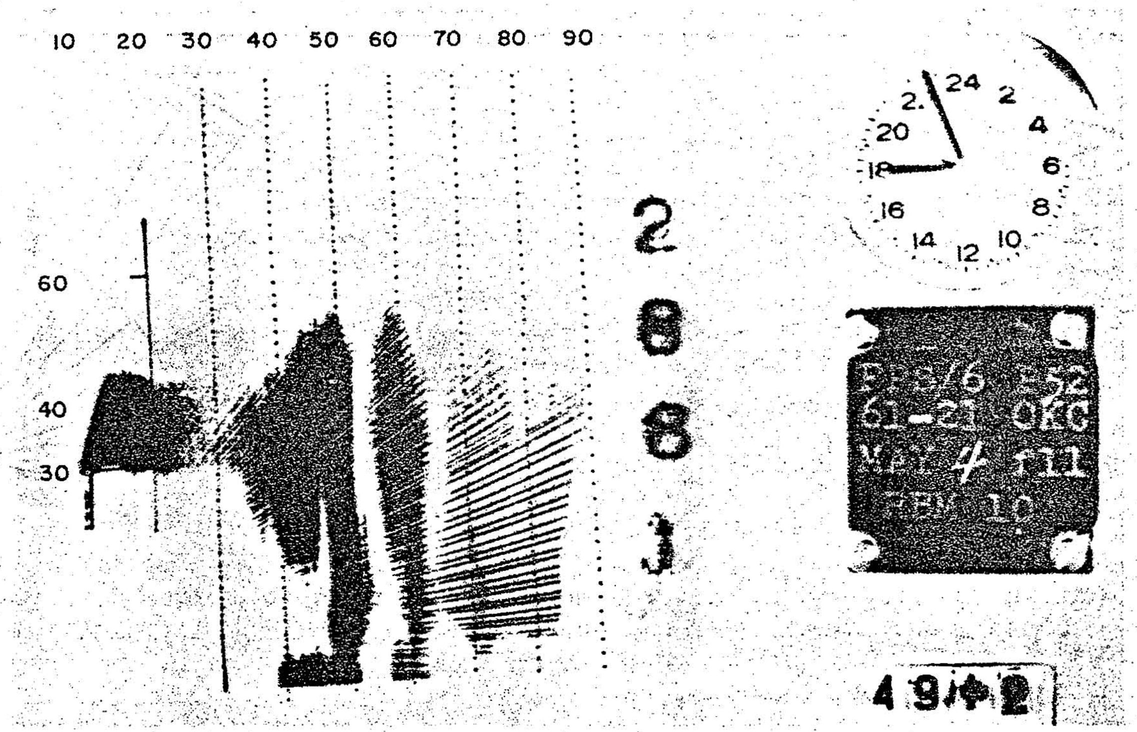

Figure 11. -RHI echo photograph of chimney 2 at its maximum echo-free height of 24,000 ft. at a range of 46 n. mi., azimuth 288°. Height markers at the left in photo are 30,000 ft. and 60,000 ft. Echo motion is toward left.

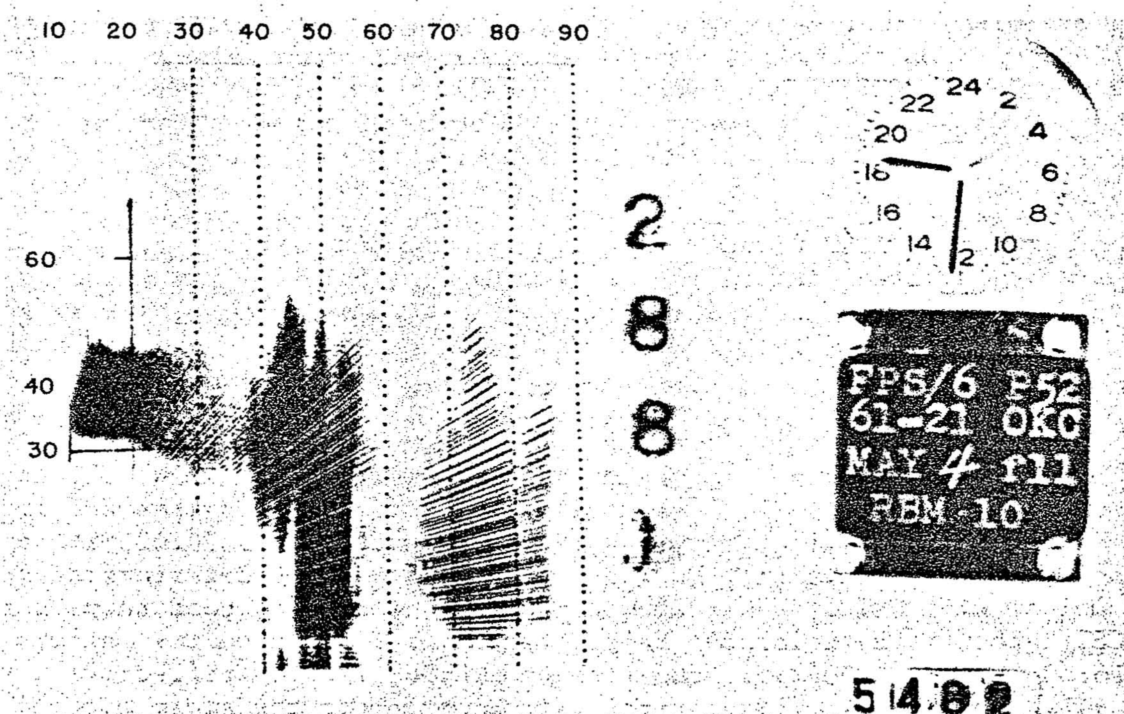

Figure 12. -RHI echo photograph of chimney 3 (range 45 n. mi., azimuth 288°). Echo-free height of chimney is 21,000 ft. Height markers are 30,000 ft. and 60,000 ft. Echo motion is toward left.

Chimney 3 formed at 1810 CST in the overtaking echo that merged with the main storm, around the time that the two echoes were merging. It maintained the direction from the WNW of the western echo, cutting across the path of chimney 2. It also had a wall from the beginning. By 1824 CST, 14 min. after first detection, it was judged to have an "excellent" shape and continued that way for the following 50 min., then deteriorated rapidly after 1914 CST. Figure 12 shows the characteristic shape, remarkably similar to chimney 2. At its maximum height at 1907 CST the echo-free area extended upward to 23,000 ft. and the low-reflectivity echo penetrated further to 30,000 ft. The maximum lateral extent, also at and just before 1907 CST, was estimated to be 7 mi. The average echo-free height throughout the existence of chimney 3 was 17,000 ft.

During the deterioration phase, the chimneys (and their attendant walls) slowed down and slid off to the left, toward the center of the storm. Figure 1 shows that chimney 2 even reversed direction a bit, moving away from the radar after 1830 CST. This behavior is surprisingly similar to the tracks of tornadoes in the Fargo, North Dakota storm that Fujita (1959) plotted. It may be that as the chimney circulation and any attendant tornadoes deteriorate, they lose contact with the mid-troposphere and come under the dominant influence of the low-level inflow, which in this case as well as in the Fargo storm was from the south to southwest.

Browning and Ludlam found the predominant tower to be located above the wall or within 1½ mi. behind it. In the Geary storm, tower (q) remained the maximum during the best part of the lifetime of chimney 1, and was located within 2 mi. of the chimney, though sometimes ahead of it. During the well established period of chimney 2, the maximum top was almost always tower (u) until later in the period when tower (α), an outgrowth of (u), shared the maximum position. Tower (u) started near the wall of chimney 2 but moved slower and fell four miles behind the wall before it disappeared in complete capitulation to tower (α). While it was prominent, tower (α) varied from 0 to 3 mi. behind the wall, though it first appeared 2 mi. ahead of the wall. The tower associated with chimney 3 was (β), and it frequently was located directly over the wall and always within 1½ mi. ahead of or behind it up to 1850 CST, after which time tower continuity was lost. During the life of tower (β) it was the highest one only about half the time. Thus, the tower activity during the "wall" phases tended to follow the general pattern of the Browning and Ludlam model, but was not nearly so steady-state.

7. STREAMERS

Another of the interesting features in the overhang area were streamers which fell into the otherwise echo-free region and sometimes hit the ground. Early in the echo lifetime the streamers, falling from the right forward sector, tilted slightly back toward the center of the storm as they fell from 30,000 ft. As time went on the level from which the streamer trails departed from vertical fell to about 20,000 ft., and they tilted more sharply.

The greatest curving away from vertical fall was in the forward edge of the overhang. For example, at 1645 CST a streamer near the central part of the right flank of the storm bent ½ mi. to the west (toward the center of the

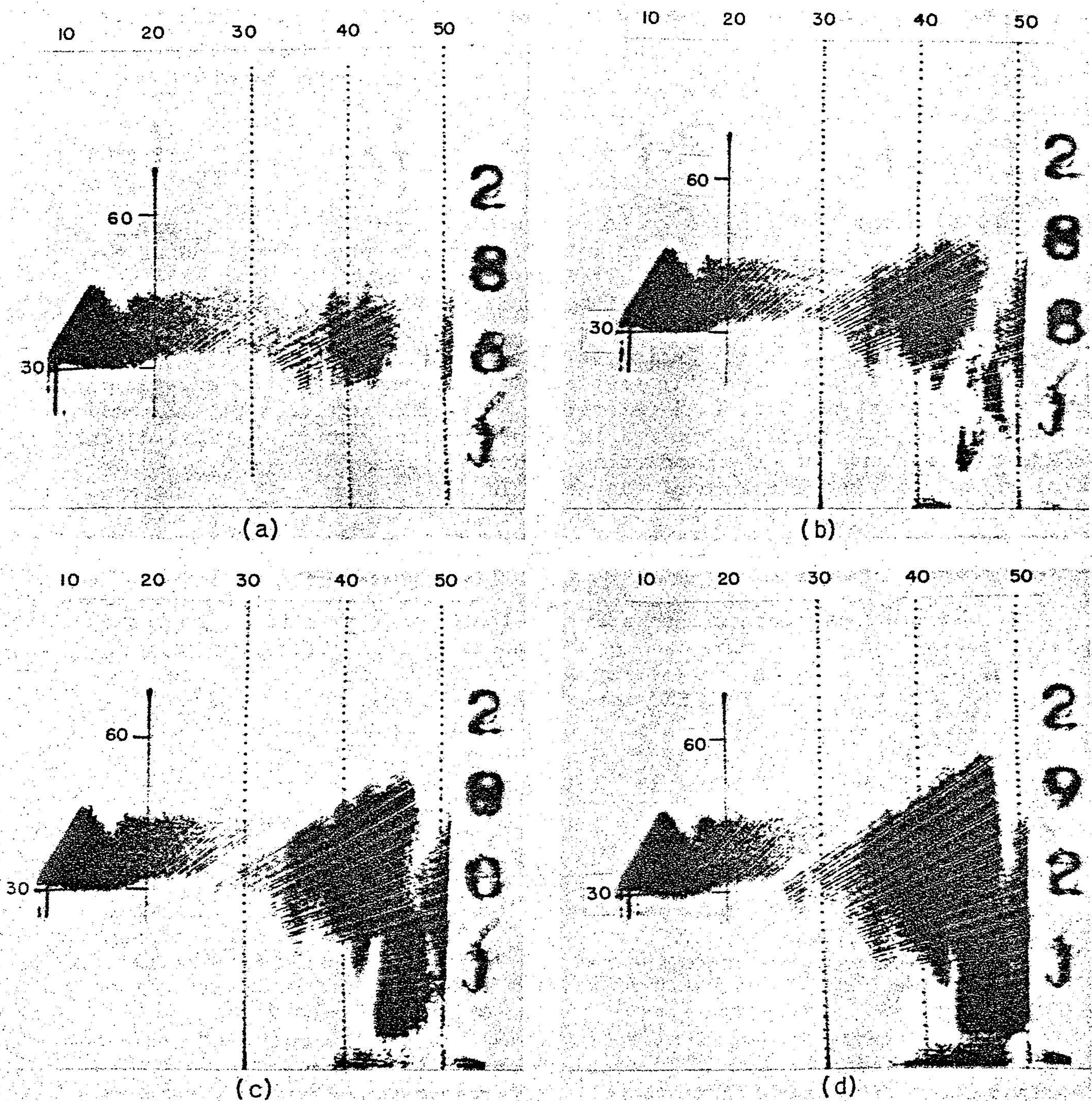

Figure 13. -RHI echo photographs at 1700:30 CST, taken at 2° azimuth intervals, showing the nature of the overhang and the streamers falling below it in the period prior to the development of a chimney and wall. Height markers are at 30,000 ft., 40,000 ft., and 60,000 ft. Storm is moving toward the left (generally towards east). Figure 13a, azimuth 268°, is a vertical slice across the southern, or right flank: subsequent pictures penetrate northward, into the center of the storm. Tips of streamer trails, which originate on the right flank, at first fall northward toward the center (figs. 13a and 13b) and eventually spiral westward toward the rear of the storm at lower altitudes (figs. 13c and 13d). Figure 13c, from which the tracing of figure 7 was taken shows the typically greater bending to the rear in the forward streamer compared with the streamers located toward the rear of the storm.

right flank) in falling from 15,000 to 8000 ft. Another streamer farther to the east bent one mile to the west as it fell from 15,000 to 6000 ft., and the easternmost or farthest forward streamer bent 1½ mi. to the west as it fell the same distance.

In another example, illustrated in figure 13, the streamer on the east (or forward) side tilted 2 mi. to the west from 15,000 ft. to 6000 ft. while the large streamer near the center tilted only about ½ mi. to the west from 15,000 ft. down to 8000 ft.

The streamer trails appeared to be roughly parabolic, with no appreciable discontinuity in slope or in intensity on the way down to indicate a bright band at the melting level. It thus seems likely that they were composed of small hail and graupel, but not snow, above the 0° C. isotherm. Variations in the slope of the streamer trails would seem to be related closely to variations in the inflow velocity under the overhang, since the range of trail slopes in the high-reflectivity streamers greatly exceeds the probable range of particle fall velocities where the particles have Z_e well above 10^3 mm^6/m^3. In fact, the trails slope greatest during the most active stage of the storm when the production of precipitation is likely to be excessive and reduce the chance of the reduction of fall speeds by evaporation. When chimney 2 was at its peak, at 1756:30 CST, the ESE or forward edge of the large easternmost streamer bent 5 mi. to the WNW in falling from 15,000 to 5000 ft. (fig. 11).

As the storm approached the radar and the azimuth resolution increased, streamer trails could be observed bending normal to the radar beam as well as along it. For example, in falling from 24,000 ft. to 4000 ft., the bottom tip of a streamer at 1903 CST apparently bent 3 mi. toward the northeast down to 14,000 ft. and then another 3 mi. toward the north during the lower half of its fall. The storm was moving toward ESE. This cyclonic corkscrew motion was apparent to some degree in nearly all trails that could be observed at three or more azimuth angles.

Schematic views of the high-reflectivity part of the Geary storm at 1800 CST are given in figure 14. In plan view, the tips of two streamers are shown curving in towards the chimney-wall location as they fall under the overhang (unshaded area of 30,000-ft. echo). The forward streamer tip shows the greatest cyclonic curve to the rear as well as the greatest tilt in the lower altitudes.

At near ranges, the outflow from the wall echo was apparent by variations in vertical slope of its leading edge and its right or southern flank. At 1903 CST the wall echo extended near the ground about one mile forward and very roughly 3 mi. to the right of its position at 17,000 ft. As Ward was returning to Oklahoma City following his tornado observations, he accidentally traversed the wall echo of chimney 3, fortunately somewhat to the rear of the forward edge. He encountered heavy rain and small hail with westerly winds estimated at 60 kt. This was undoubtedly a part of the outflow from the wall echo.

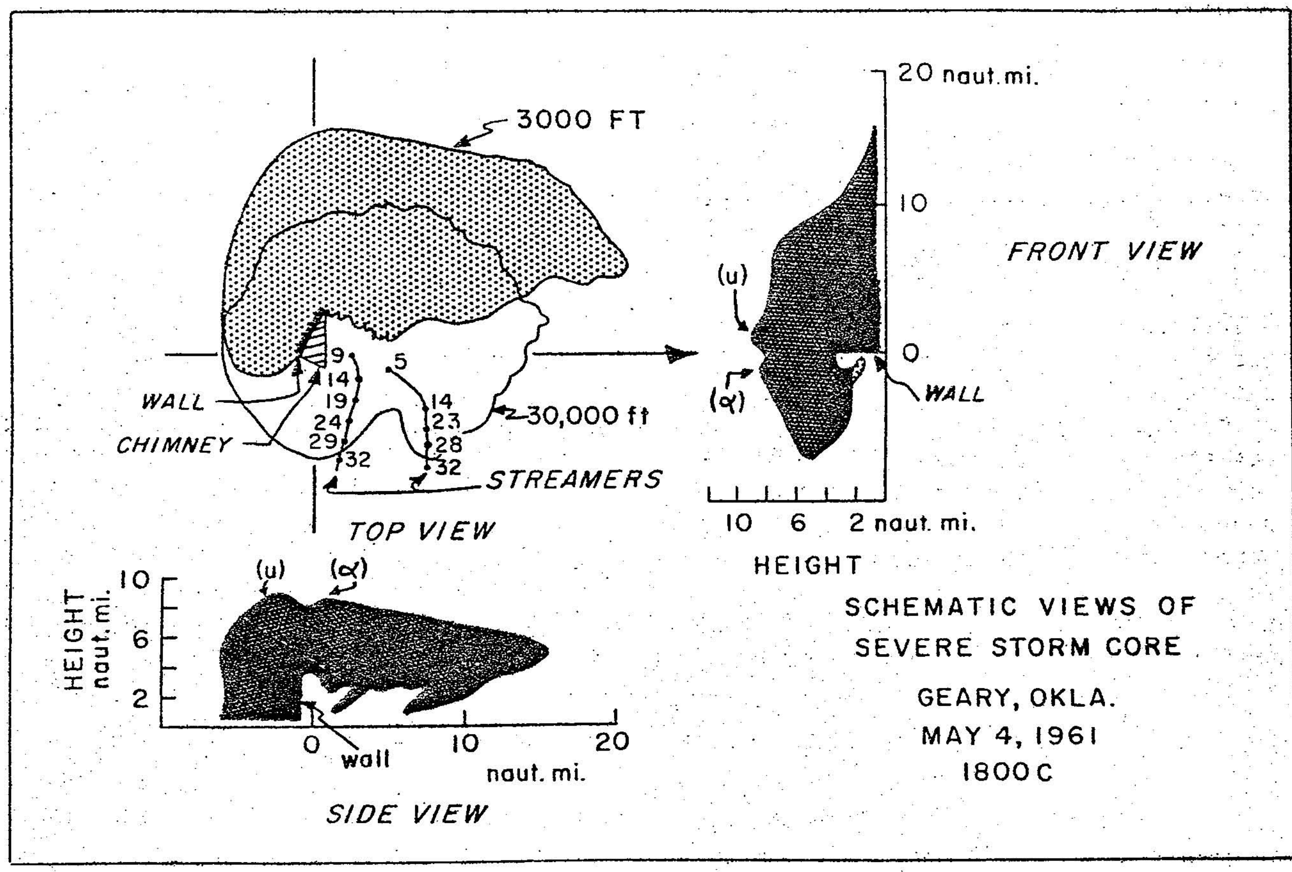

Figure 14. —Schematic views of high-reflectivity echo in Geary tornado storm at 1800 CST. Top view shows contours at two altitudes. Arrow indicates storm motion. Note the "tornado hook" in the 3000 ft. contour (dotted) toward the right rear, behind the wall: it is poorly defined here because of the wide azimuthal beam pattern and the smoothing by interpolation of points separated 2° in azimuth. But there is no doubt that the tornado hook which is defined well on PPI is simply the wall echo at low altitude. The chimney is denoted by the hatched area; it is wedge-shaped in plan view and narrows toward the storm center. The overhang is the clear unstippled part of the 30,000-ft. echo. The trajectories of two streamer tips are noted, showing cyclonic spiral shape as they fall into the chimney-wall area. (The numbers on the streamers are the heights of the tip in thousands of feet.) Front and side views show towers (u) and (α), and streamers falling beneath the overhang.

8. CONES

During the study of the streamers, an occasional "cone" or apparently vertical and symmetric streamer was noted just ahead of the wall and almost counterpoised below the chimney. An excellent example has been depicted in figure 15. Apparent continuity was found for five cone trajectories. These are plotted in figure 16, with a thicker track signifying a higher quality of appearance.

The cone echoes have the general appearance of a funnel, though they are much more stubby and have a much larger apex angle than the usual tornado. They are more similar in size and shape to the region of depressed cloud base often observed above tornadoes. The cones typically extend down from the overhang to altitudes between 5000 and 12,000 ft. On rare occasions there is a very thin vertical projection below, and once a thin "stalagmite" was observed projecting upward from the ground toward the cone base above it.

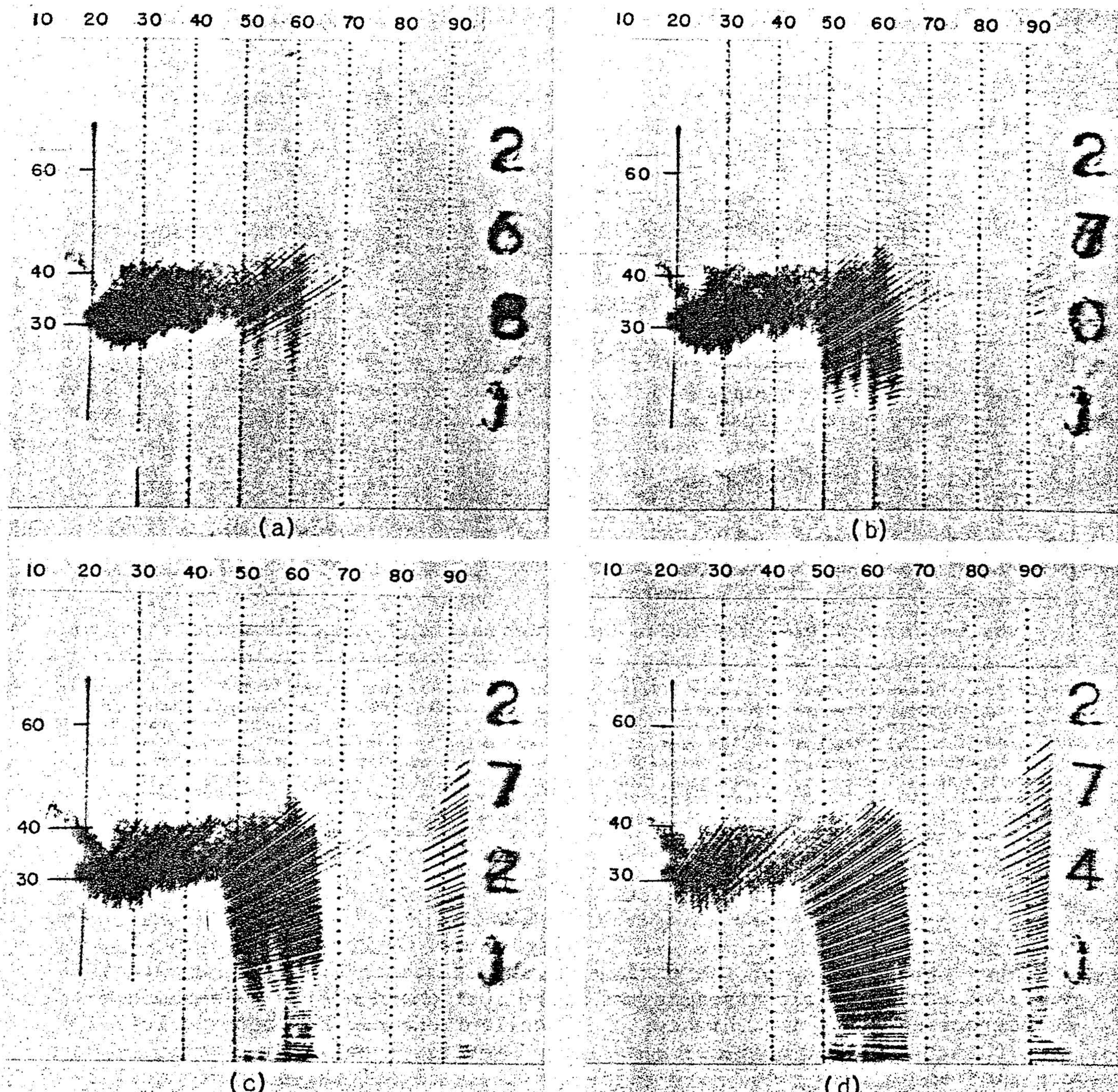

Figure 15. (a to d): -RHI echo photographs at 1808 CST, taken at 2° azimuth intervals, showing detail of chimney and wall. Range markers are at intervals of 10 n. mi. Height markers visible on all photographs are at 30,000 ft. and 60,000 ft. Echo moves to left. Tower (u) reaches an altitude of 58,000 ft. on figure 15d at 292°, range 46 n. mi. Figure 15b shows an intense part of the wall echo near the ground appearing to the right and forward of the center of mass of the major part of the wall photographed subsequently in figures 15c and 15d; this may be an indication of low-altitude outflow spreading out toward the right and front of the storm from the intense precipitation area denoted by the wall echo. Note also the marked tilt of the chimney toward the rear in figure 15c. The inclination is actually 25° away from vertical, though on the distorted scope presentation it appears more nearly vertical because the horizontal scale is stretched by a factor of 3.4.

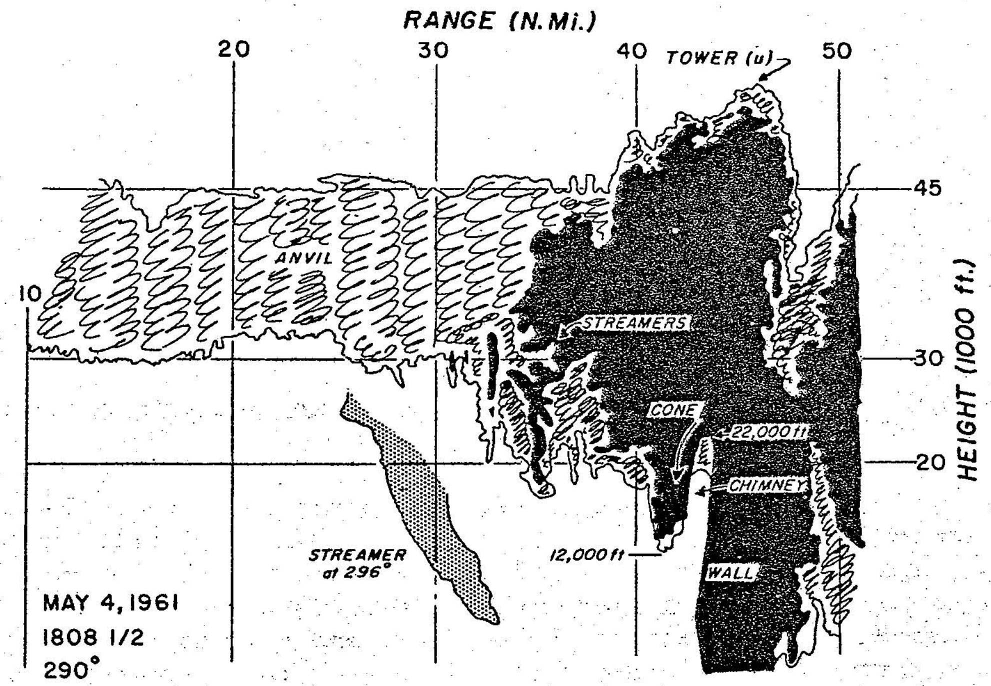

Figure 15. (e) –An explanatory tracing of figure 15c (photograph at 290°) showing location of wall at the rear of the overhang, chimney just ahead of the wall, and streamers and cone descending beneath the overhang.

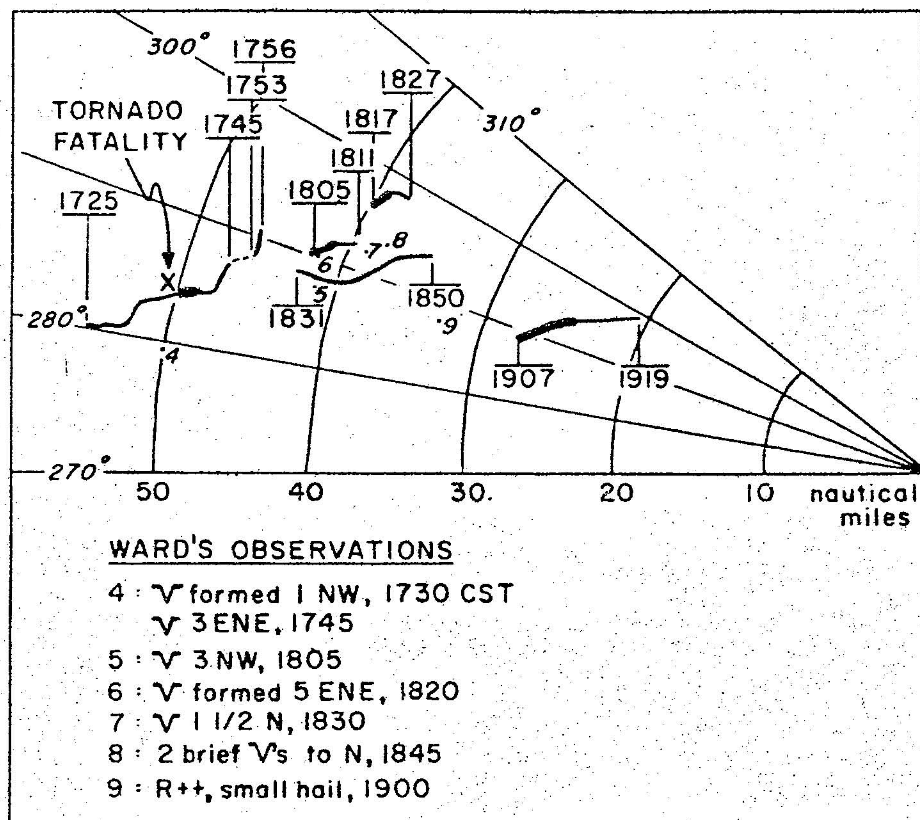

Figure 16. –Trajectories of cones. Thickened track indicates high-quality appearance of cone. Cones during 1725-1756, 1805-1811, and 1817-1827 CST were associated with chimney 2. During 1831-1850 and 1907-1919 CST the cones were associated with chimney 3. Numbers 4 through 9 locate Ward's observation points.

The cones are associated fairly well in time and space with the observed tornadoes, though it is clear that these observations do not establish cone echoes as reliable tornado indicators. Referring to figure 16, Ward's observations at position 4 correlate quite well with the earliest cone trajectory, although there is a distance discrepancy. At position 5 the distance error is not large but the direction to the cone is toward the north, instead of northwest to the tornado as Ward observed. Position 6 checks almost exactly. Positions 7 and 8, however, do not indicate any close relation between tornadoes and cones.

9. SUMMARY

The most important finding in this study is the striking similarity in echo features of the Geary, Oklahoma storm to the characteristics of a severe hailstorm in England discovered by Browning and Ludlam and incorporated in their convection model. The differences are mainly in detail. The principal features common to both storms are: (1) the overhang, (2) wall, and (3) echo-free vault (or chimney) which, according to the Browning-Ludlam model, signify, respectively: (1) an area of ascending inflow, (2) a region of heavy precipitation and descending air with strong outflow, and (3) the location of the most intense portion of the updraft at the base of the overhang. Another feature common to both storms was the occurrence of the maximum tower tops directly above the wall or within a very few miles of this line. However, the Geary storm was more complex and less steady than the Browning-Ludlam model and suffered a merger with an overtaking storm. Also, no conclusive information was gained on the degree of updraft tilt in the Geary storm. Finally, the Geary storm produced frequent streamers which descended in cyclonic spiral motion through the base of the overhang region.

The observed tornadoes were associated in a general way with one of the two well-formed chimney and wall configurations, occurring in a zone of maximum shear (in accordance with the Browning-Ludlam model) between ascending inflow and outflow from the descending air in the wall echo. This is consistent with the impression gained by Ward (1961) who stated that "tornadoes formed along the shear line between the southerly surface winds and the northerly outflow of rain-cooled air, underneath a convective cell".

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REFERENCES

1. Atlas, D., and F. H. Ludlam, "Multi-Wavelength Radar Reflectivity of Hailstorms", *Quarterly Journal of the Royal Meteorological Society,* vol. 87, No. 374, 1961, pp. 523-534.

2. Bigler, S. G., "Observations of a Tornado Using the AN/CPS-9 Radar", *Proceedings of the Seventh Weather Radar Conference,* American Meteorological Society, Miami Beach, Fla., 1958, pp. K1-K5.

3. Browning, K., and F. H. Ludlam, "Radar Analysis of a Hailstorm", *Technical (Scientific) Note No. 5,* on Contract AF 61(052)-254, Imperial College of Science and Technology, London, 1960.

4. Browning, K., and F. H. Ludlam, "Air Flow in Convective Storms", submitted to *Quarterly Journal of the Royal Meteorological Society,* 1962 (in press).

5. Donaldson, R. J., Jr., "Analysis of Severe Convective Storms Observed by Radar", *Journal of Meteorology,* vol. 15, No. 1, Feb. 1958, pp. 44-50.

6. Fujita, T., "A Detailed Analysis of the Fargo Tornadoes of 20 June 1957", *Research Paper* No. 42, U. S. Weather Bureau, 1960, 67 pp.

7. Ligda, M.G.H. "The Synoptic Analysis and Forecasting Applications of Radar Weather Observations", *Final Report,* under Contract AF 19(604)-1564 (AFCRC TR 58-251). Department of Oceanography and Meteorology, Texas A. & M. College, College Station, Texas, June, 1958, 123 pp.

8. Ward, N. B., "Radar and Surface Observations of Tornadoes of May 4, 1961", *Proceedings of the Ninth Weather Radar Conference,* American Meteorological Society, Kansas City, Mo. 1961, pp. 175-180.

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