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A STUDY OF
SEVERE STORM ELECTRICITY
VIA STORM INTERCEPT

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ABSTRACT

We have used storm electricity data, radar data, and visual observations both to present a case study for a supercell thunderstorm that occurred in the Texas Panhandle on 19 June 1980 and to search for insight into how lightning to ground might be related to storm dynamics in the updraft/downdraft couplet in supercell storms. We observed that two-thirds of the lightning ground-strike points in the developing and maturing stages of a supercell thunderstorm occurred within the region surrounding the wall cloud (a cloud feature often characteristic of a supercell updraft) and on the southern flank of the precipitation. Electrical activity in the 19 June 1980 storm was what we consider to be typical for an isolated severe convective storm; the storm was atypical in that it was a right-mover. Lightning to ground reached a peak rate of 18/min and intracloud flashes were as frequent as 176/min in the final stage of the storm's life.

INTRODUCTION

Ground intercept of severe convective storms as a scientific project began in 1972 by the National Severe Storms Laboratory (NSSL) in collaboration with the University of Oklahoma (Golden and Morgan, 1972; Lee, 1981). Initially, photographic documentation of cloud features and correlation of observations with NSSL's Doppler radar studies was a primary goal. Observations from vehicles moving with the storms is still an integral part of severe storm study and visual observations facilitate understanding of both the storm structure and the driving dynamics (Davies-Jones, 1981a).

As a sidelight to their main mission in the first years of storm intercept, storm observers often keyed on lightning as a qualitative indicator of storm severity. A keen observer with a knowledge of storm evolution could often correlate cloud-to-ground (CG) lightning with co-evolving cloud features (which in turn were often correlated to a storm's structure and its dynamics). In spite of the inherent inadequacies and inaccuracies of visual sightings of lightning, visual documentation was sufficiently complete after a few years of formal intercept to increase our knowledge of temporal and spatial occurences of CG lightning in severe storms (Davies-Jones and Golden, 1975; Arnold and Rust,1979; Rust, et al. 1981a,1981b).

Equipping a mobile laboratory that could be used to track storms and quantify lightning observations was a logical extension of the intercept effort, and in 1978 a group from the University of Mississippi (UM) joined with NSSL scientists. The UM/NSSL mobile lab was operated during much of the severe thunderstorm season in central and western Oklahoma in 1978 - 1984. Initially, the primary goal was to document accurately lightning and other electrical parameters that might be correlated with storm dynamics and structure, but the work has been extended to include the flight of instrumented balloons (Marshall and Rust, 1983). Years of visual observations leave little doubt that correlations do exist, but definitive measurements have been slow in forthcoming.

The strategy of storm intercept is to position the mobile lab within a storm's surface inflow where view of the cloud features is unobstructed and to move with the storm as it evolves. Figure 1 shows three views of a "typical" isolated supercell storm. In each view, a representative tracking position is marked with an *. It is primarily, although not exclusively, from a similar vantage point that other intercept teams have learned to interpret cloud features in terms of structure and dynamics (Davies-Jones, 1982). (Moller (1980) gives a good description of the visual features of severe storms.)

Other than an initial article in 1979 by Arnold and Rust reporting on preliminary measurements, no reports have been made in the literature that can be used to evaluate storm intercept as a means for quantitative electricity measurements. In this paper, we present and discuss observations made from the mobile lab on 19 June 1980 for an isolated severe storm that occurred in the Texas Panhandle.

A. STORM ENVIRONMENT ON 19 JUNE 1980

On the morning of 19 June 1980, the upper level steering winds over the central United States were from the northwest. A minor shortwave disturbence over the intermountain region was moving toward the southern plains states. At the surface, a stationary frontal system lay from eastern Colorado across southern Oklahoma. Very moist unstable air was being advected north and westward along the frontal surface. During the afternoon, the approaching shortwave aided the convergence along the stationary frontal boundary and triggered thunderstorms along much of the front. The airmass was very unstable with quite warm moist air at the surface and cold air advection aloft. The evening sounding at Amarillo, Texas revealed that a parcel lifted from near the surface would experience a 10 C temperature excess at a height of 500 mb (a lifted index of -10).

The summary of conditions at 1800 CST is shown in Figure 2. The storm track shown in Figure 5 indicates that the storm of interest, already severe, had formed ahead of the shortwave along the frontal boundary and was being 'fed' by low-level moisture from the southeast. Mid-tropospheric windspeeds were only 10 to 15 m/s, although maximum winds at the tropopause increased to 35 m/s. In general, the environment was typical of late spring severe weather situations in the southern plains i.e., large thermal bouyancy and weak to moderate dynamics. Under such conditions large scale severe tornado outbreaks are not likely, but isolated severe thunderstorms with frequent lightning, large hail, strong winds, and minor tornadoes often occur.

B. STORM INTERCEPT

B1. Storm Tracking on 19 June 1980

Several hours prior to storm development, two intercept vehicles left Norman, Oklahoma and moved towards the Texas Panhandle. One vehicle, from NSSL, was equipped for photographic documentation of visible storm features. The second vehicle, the UM/NSSL mobile lab, was equipped for storm electricity measurements. Both teams made visual contact with the storm at about 1630 CST. Once positioned beneath the storm at approximately 1745 CST, the teams backtracked as the storm moved almost directly towards the mobile lab with its wall cloud in front of large column of advancing precipitation. (A low cloud in the storm's inflow is called a wall cloud if rotating and a pedestal cloud if not.) A photograph of the wall cloud at 1846 CST is shown in Figure 3. The wall cloud had a somewhat ragged appearance but existed as a prominent feature for over two hours.

Data aquisition was begun at approximately 1749 CST and continued until almost 2100 CST. After 1900 CST the almost perfect vantage point was interrupted by towns, hills, and the lack of appropriate roads. Our most complete data set was recorded during the interval from 1745 - 1901 CST while the mobile lab remained in the surface inflow region and maintained good visual contact with the region of the storm actively producing CG lightning. Evolution of the visual features during this period, both of lightning and of clouds, was prominent enough to allow us to offer a reasonable interpretation of the changing storm features.

B2. Instrumentation

The instrumentation used in the mobile lab included: a TV camera with a variable angular view of 20°-35° for documentation of both CG lightning and cloud features; an electric field mill for measuring the atmospheric electrostatic field; three lightning field change antennas (10 s, 3 ms, and 100μs decay times) for measuring the electric field changes produced by lightning; a probe for measuring corona current; a 3 MHz sferics reciever for measuring radiation associated with electrical discharges; and a sensor for optical transients. Three types of analog recorders were used to record the data as shown in Figure 4: an eight track strip-chart which recorded two sensitivities of 3 Mhz sferics, corona current, electric field, time code, and electric field change detected by the 10 s field change antennas; an eight track instrumentation tape recorder with an FM bandwidth, at 19 cm/s, of 0-5 kHz, which recorded electric field changes, two sensitivites of 3 MHz sferics, and time code; voice documentation; and two VHS format video recorders, one for TV and the other modified for recording with a 3 MHz bandwidth the output of the 100 s lightning antenna.

C. RADAR ANALYSIS

C1. Storm Evaluation from a WSR-57 Radar

The film from the National Weather Service WSR-57 radar at Amarillo, Texas was analyzed to document the lifetime of the storm. The storm track shown in Figure 5 indicates that the storm split at 1630 CST shortly after formation. As is common with splitting storms (Browning, 1968), one section moved left and was not significant while the other section moved right and continued to intensify. The mean wind at Amarillo (AMA) at 1800 CST was from 260 at 13 m/s. The storm, during its period of greatest strength, moved from 330 which was far to the right of both the mean wind and wind at any level in the environment. Before the storm dissipated at 2320 CST, its motion turned more to the east.

Radar characteristics identify the right-moving storm as a classic supercell (Browning, 1965a). It was essentially an isolated storm for all of its lifetime and continuously produced strong reflectivities, a high top, and a periodic hook-like echo indicative of cyclonic circulation. Two less significant radar echoes did merge with the storm at the times indicated in Figure 6. The influence of the mergers upon the storm structure is not known, but it is possible that the intensification observed after 1800 CST was a consequence of cell merger. Radar reflectivities suggest that the storm was a prolific producer of large hail, and visual reports by the intercept teams and the public indicate that there was a swath of severe hail damage between 1900 - 2000 CST. Before and during the hail swath, a radar side-lobe "spike" was detected at the edge of the echo. Such a spike is evidence for the presence of large quantities of hail, perhaps large. The continuous existence of tall tops (several km above the tropopause) and very high reflectivity values (55-60 dBZ) make it likely that some hail fell from the storm over a large portion of its lifetime, even at times other than those indicated in Figures 5 and 6.

C2. Doppler Radar Data

Doppler data from the 10 cm wavelength radar at NSSL were collected over a segment (1845 - 2200 CST) of the storm's mature stage. During this period, the storm was about 300 km from the radar, a rather large distance at which to extract meaningful characteristics. Fortunately, the narrow beamwidth (0.8 deg) of the radar antenna makes it possible even at long range to resolve larger scale motions such as mesocyclone rotation (typically 10 km in diameter) and radial divergence at the updraft summit (17-20 km in height). (See Burgess, et al. (1979) for a discussion of single Doppler signature recognition.)

Divergence of the radial velocity component at updraft summit is a qualitative measure of the updraft speed. The radial divergence near 1900 CST shown in Figure 7 suggests that there was a strengthening within an already strong supercell updraft. Intensification of the updraft was evident to the intercept teams at 1825 CST as a marked increase in surface wind speed. The sampling criteria that was used limited the amount of divergence data: there is none after 1945 CST. Continuity in updraft rotation during most of the mature stage was implied both by the periodic existence of hook-like echoes and the visual observations from beneath cloudbase including a longterm cloudbase rotation, a funnel cloud (1830 CST),and a tornado (2027 CST). A longlasting mesocyclone was confirmed by the continuous existence of a vortex signature during the single Doppler collection interval shown in Figure 7. The three peaks in the cyclonic shear data suggest that there were three peaks in rotational magnitude; this was further supported by observations of rotating wall cloud features made by surface intercept teams. In fact, observations by intercept teams of wall cloud rotation prior to the period of Doppler radar data acquisition indicated that a mesocyclone existed as early as 1750 CST and persisted for 30 to 45 min.

D. OBSERVATIONS

D1. Lightning and Electric Field Data

Electric fields, changes in electric fields, and documentation of lightning strikes to ground are the records pertinent to this paper. Measurements and observations were made from the position marked by an asterisk in Figures 1a, 1b and 1c. The shaded area in Figure 1b is the approximate region over which the CG lightning was observed, both visually and on TV. (Throughout the data aquistion period, flashes to ground outside of this region could not be seen.) Figure 8 shows both the CG lightning flash rates and the storm parameters determined from radar analysis. Flashes to ground were verified either from visual sighting and/or from the TV record. The intracloud (IC) flash rates (Figure 9) were estimated from a continuous analog record (with a time base of 2.8 cm/s and three different sensitivities) of the electric field change. Estimates of the total CG flash rates were made from the same record, and the results are shown in Figure 10. By comparing the documented CG flash rates with those determined from the analog record, we estimate that 66% of all CG flashes were documented over the entire observational period. Based on visual similarities between this storm and many others that we have tracked, we suspect that our combined visual and TV sightings of CG lightning represent a constant fraction of the total CG flashes over the entire three hour observational period. We were in the best position to view both CG lightning and wall cloud features from 1749 - 1900 CST; we emphasize this period in the discussion section.

Early (1753 - 1843 CST) during the observational period, we observed twenty three single stroke flashes. Single stroke flashes were observed throughout the observational period, but the ratio of single to multiple stroke flashes was greater early in the observations (Figure 10). The flashes were characterized visually by their brightness, multiple branching, and quickness to the eye. A typical electric field change measured with an antenna with a 10 s decay is shown in Figure 11.

A continuous record was made of the electric field at the mobile lab as it moved beneath the storm's rainfree base. Figure 12 shows a portion of the field record for a time period when the mobile lab moved very near to the edge of the wall cloud (shown in Figure 3). The data have been averaged over 30 s intervals and identifiable lightning transients were not included in the graph. As the SE edge of the wall cloud approached the lab's position, the electric field increased abruptly from 2 kV/m (a typical value) to 23 kV/m.

D2. Summary

Examining the CG flash rate data shown in Figure 9, one can see that there are three broad peaks; between 1745-1825 CST, 1825-1915 CST, and 1915-1945 CST. When compared with the CG flash rate data from the slow antenna record, the latter two peaks are in agreement, but the first peak is shifted forward in time by about ten minutes. We can explain the apparent discrepancy in the following way: First, the initial part of the slow antenna data was obliterated by 60 Hz noise from nearby power lines, and second, the storm was initially very distant (30-40 km when we began data acquisition). CG flashes, which were clearly visible, might have been beyond the range of the slow antenna. Consequently, the flash rates measured initially by the slow antenna are probably low; this period from 1745-1825 CST is the only period where the visual observations are better than the field change data.

Temporal variations in the IC:CG ratio shown in Figure 9 also represent believable values since both flash types were identified from field change data acquired with comparable efficiency. Actual values of the ratio might be high since field changes produced by in cloud discharges are often greater than those produced by flashes to ground, particularly near the end of a storm's life. Further, it is often difficult to distinguish pure in-cloud events from CG's having large continuing currents. The IC:CG ratio versus time suggests that there were always more IC than CG flashes per 5 minute interval. Trends in the data suggest that as the IC rate increases then the CG rate diminishes and visa versa.

The maximum radar reflectivity as determined from the Amarillo radar was between 55 and 60 dBZ over most of the observational period; the storm top remained between 17 and 18 km. The CG and IC flash rates show no variations easily correlated with maximum reflectivities. However, over the interval 1755 - 1900 CST, a careful study of the data in Figure 8 suggests that reflectivity changes might have been accompanied by similar changes in the CG flash rate. Over this time interval there was a vigorous, well defined wall cloud (and thus updraft) bordering on the SSE side of a large, well defined precipitation shaft. The Amarillo NWS WSR-57 radar at 0 deg elevation was receiving reflections from 7 km or below and hail in significant quantity and size probably existed above this altitude. Doppler data aquistion was not begun until approximately 1850 CST, and our knowledge of the evolving dynamics before this has to be inferred from the Amarillo radar and visual observations.

Some major implications of the lightning results shown in Figures 8, 9, and 10 (for the time interval 1750-2005 CST) are listed below. The implications are:

1. Approximately 66% of all CG lightning in the storm was seen from under the rainfree cloud base near the wall cloud.

2. Approximately 28% of all CG flashes were single stroke; and during the early stages of storm development, 80% of CG flashes were single stroke.

3. Approximately 27% of all flashes were CG and the peak IC flash rates appear to have occurred when the peak CG rates were at minima.

Similarly, some important features of the radar data are (all times have been given to the nearest 5 minutes to facilitate comparison with lightning rates):

1. Approximatly 1755 CST a small cell merged with the main storm cell.

2. At 1800 CST there was a 4 dBZ increase in reflectivity at low levels.

3. Near 1805 CST the maximum cloud top was reached.

4. The maximum cloud top decreased at 1825 CST.

5. The radar reflectivily increased 4 dBZ at 1800 CST, decreased 4 dBZ again at 1830 CST, increased at 1840 CST, decreased again at 1850 CST and showed no further changes greater than 0.5 dBZ/min for later times; the radar reflectivity slowly increased 3 dBZ between 1915-1930 CST.

6. A second cell merger occurred from 1930-1945 CST.

7. Radar reflectivity spikes were observed from 1800-1820 CST and 1905-1955 CST.

8. Radar hook-echoes were observed over the intervals 1820-1835 CST and 1855-1900 CST.

9. The estimated divergence was increasing when Dopplar radar data acquistion began at 1850 CST.

10. Peaks in the cyclonic shear were observed at 1915 CST and 1950 CST (after 2000 CST two other peaks were observed).

Prominent visual features were noted and recorded by the intercept teams, and are listed below.

1. At 1745 CST a wall cloud was observed.

2. From approximately 1815-1825 CST there was rotation of the wall cloud.

3. At 1815 CST marble sized hail fell within the surface inflow at a distance 3-5 km from the precipitation shaft.

4. A small funnel cloud was observed at 1825 CST.

5. Surface inflow winds increased significantly at approximatly 1830 CST; estimated winds increased from 20 m/s to 30 m/s.

6. At 1830 CST the wall cloud was again observed to rotate and had a more laminar appearance than earlier; rotation continued at least until 1845 CST.

7. At 1850 CST marble sized hail again fell within the surface inflow region at a distance well removed from the precipitation shaft.

8. A small funnel cloud was observed at 1855 CST and again the wall cloud began to loose its organized appearance. Shortly after 1900 CST a second funnel was sighted.

After 1900 CST we were not in a position favorable for making visual observations.

E. DISCUSSION

E1. Lightning and Storm Structure

Over seven seasons of storm electricity intercept we have documented simultaneously lightning, visual cloud features, and radar reflectivities. As a consequence we have formed some impressions about how a storm's structure (and perhaps its dynamics) might relate to its lightning activity. Our conceptual view of how cloud features and lightning co-evolve in real time has been of value in both data aquisition and storm tracking. Whether or not our concepts have much to do with supercell thunderstorm electrical activity remains to be seen. But we and other storm trackers have observed that CG lightning is often a good indicator of both a storm's severity and its dynamics during its developmental stage (Arnold and Rust, 1979; Davies-Jones, 1981b). We are of the impression that CG lightning rates vary markedly between storms, but temporal and spatial occurrence does not. Lightning to ground seen from beneath the rain free cloud base can often be interpreted as a signal of changes soon to be evident in storm cloud features. In the paragraphs below we present some of our perceptions and conceptions of how electrification in isolated supercells might evolve. Cloud-to-ground lightning has influenced us more than intracloud because IC flashes are difficult to identify in real time.

A simplified drawing of a supercell thunderstorm is shown in Figure 13, which along with Figure 1 is a convenient reference in the following discussion. Spiraling upward arrows in Figure 13 represent the main updraft, and the broad downward arrow depicts the precipitation cooled downdraft. The shaded area within the storm corresponds to heavy precipitation both aloft and at the ground.

During the mature stage of a severe storm a vigorous updraft excludes precipitation (Browning, 1965b). A well defined region of low radar reflectivity (weak echo region (WER), e.g., see Browning, 1965b; Lemon, et al., 1975) is observed within the main updraft. A wall cloud is a feature below the cloud base that marks the low level portion of the updraft. If updraft winds decrease, then an increasing amount of precipitation reaches the ground in the region around the wall cloud. Most often this marks the wall cloud's demise.

Two processes are at work to weaken the updraft. First, precipitation loads the top of WER. Sufficiently massive water and ice particles will fall through the updrafting air. As a consequence, less low level, warm, moist air is carried aloft and the storm weakens. Second, inflowing low-level moist air is throttled by intruding mid-level, cool, dry air which comes to ground and occludes the updraft. As a consequence the updraft lessens and precipitation falls through it. A more complete description of these processes can be found elsewhere; the main point here is that descent of the WER top might be evidence for a decrease in the updraft wind speed irrespective of the process(es) at work.

Descent of precipitation into the WER is accompanied by one or more changes in visual wall cloud features. Preceding any change in the wall cloud's appearance, isolated, large hailstones (marble to golfball size) are often observed under and around it at rather large distances from the precipitation shaft, and bright, multiply branched CG flashes, which appear to the eye to be very fast, strike the ground in the vicinity of the wall cloud. Some changes observed later are:

1. Ruffling of the wall cloud, i.e. a wall cloud exhibiting smooth laminar appearance (Figure 14) develops many inverted turrets which present a mammatus like appearance on its underside (Figure 15).

2. The size, both vertical and horizontal, of the wall cloud diminishes.

3. In the process of wall cloud diminution, the radius of the maximum tangential velocity of the wall cloud diminishes (Figure 16) and the angular speed increases.

4. Funnel clouds or tornadoes occur.

5. Precipitation falls through the wall cloud.

6. The wall cloud loses its organized appearance.

The principal dynamical feature that distinguishes severe convective storms from smaller, nonsevere storms is the updraft/downdraft couplet which exists in a quasi-steady state and often exists for hours. The first lightning to ground in young supercells is always seen in the main updraft. As the storm grows and continues to electrify, the region of the updraft is the most frequent for strikes. Throughout the developing and mature stages of a supercell the area over which ground strikes occur grows, but the region of the updraft remains a prominent region of CG activity.

The 19 June 1980 storm showed many of the features that are typical for an isolated supercell. A wall cloud formed at approximately 1745 CST, and CG lightning was a prominent storm feature in the rainfree region around the wall cloud by 1755 CST. The number of flashes to ground increased significantly over the next ten minute interval, during which the WSR-57 radar data exhibited a spike and a 4 dBz reflectivity increase. Although radar reflectivity at zero elevation remained high, the CG lightning rate diminished as markedly as it had increased (Figure 8). Shortly after the maximum in flash rate at 1805-1810 CST, the wall cloud showed more of a ragged structure than when first observed and it diminished in size. Usually, the wall cloud feature will be less prominent and disappear shortly after such changes. On this occassion it did not, and storm re-intensification began a short time later, perhaps as a consequence of cell merger. Within a few minutes of the changes in the wall cloud, the storm top decreased, the wall cloud rotation tightened, and hail fell through the surface inflow region. The observed changes in the wall cloud features were indications that the streamlines in the updraft were interrupted. A small funnel cloud formed on the SW edge of the wall cloud at 1825 CST.

A possible explaination of the changes in radar reflectivity and cloud features is that reflectivity increases at 1800 CST and 1840 CST (Figure 6) were produced as precipitation was lowered into a vigorous updraft. The high value of the single:multiple stroke CG rates (Figure 10) at these times suggests that the single stroke flashes might have originated from charge located along the WER/core boundary as the WER top descended. (From viewing CG lightning in several storms both with TV and the eye, we are inclined to believe that the channels of the single strokes are almost vertical.) Perhaps as the WER top descended below a critical volume (inside of which an optimum environment for charge generation and separation existed) flashes from charge centers along the WER/core boundary were less frequent.

The radar reflectivity decreased at 1830 CST, increased at 1840 CST, decreased again at 1850 CST, and after 1900 CST increased for 30 min before beginning a steady decline that persisted for 3 hrs. In large storms it is not uncommon for the updraft to pulsate. When water and ice from above the WER is lowered into the zero elevation radar beam, reflectivity increases; as the updraft surges, it pushes the precipitation above the beam once again and reflectivity decreases. Peaks in the single stroke flash rate might be interpreted as an indication that charge pockets were again formed along the WER/core boundary as high concentrations of water and ice moved through the optimum environment for charge generation and separation.

The lightning rate increase at 1830 CST was followed 5-7 min later by a more laminar appearance of the wall cloud. An increase in inflowing surface winds indicated that the updraft was intensifying. As intensification of the upraft continued, we suspect that the WER top was pushed well above 6 km. After 1900 CST our almost perfect vantage point was lost. Consequently, we have fewer visual impressions about later time periods.

If our conjecture about the occurence of single stroke flashes from along the WER/core boundary is correct, then the two peaks in the single stroke to total CG flash rates that occur at 1930 CST and 1955 CST might indicate that twice precipitation fell through the updraft.

Available Doppler radar data began about 1855 CST, but there are apparently no strong correlations between these data and the measured lightning rates. However, we do note that 10 - 15 min prior to both the hook-echoes (WSR-57 PPI display evidence for a mesocyclone) and the peaks in cyclonic shear (single Doppler evidence for a mesocyclone) there is a marked decrease in CG lightning. (Lemon, et al. (1975) reported that increased circulation in the parent mesocyclone indicates a decrease in updraft strength.) We interpret both the hook-echo and the peaks in cyclonic shear as indications that the updraft winds were diminished several times by precipitation loading.

The storm top had already reached a height of 17-18 km when our data acquisition began at 1749 CST indicating a vigorous updraft. However, the CG lightning rate was low which we interpret to mean that updraft vigor alone does not dictate the CG flash rate. Radar data indicate that about 10 min after the first CG peak at 1805 CST the rate began to decrease and the cloud top collapsed. It is interesting that the 10 min interval between the onset of a decrease in flashing rate and the cloud top collapse is the same order of time it takes for a parcel of air to rise from a height of 6 km to the already existing storm top height at 17 km. A fairly typical average updraft speed over the height interval 6 - 17 km is 20 m/s, and with this value we estimate the delay between updraft loading and the beginning of collapse to be about 9 min which is in reasonable agreement with the storm top change shown in Figures 4 and 8.

Throughout the time interval 1750-1825, the TV camera was aimed towards the wall cloud where approximately 80% of the flashes observed on TV were single stroke flashes. To the eye they were very fast, bright, and multiply branched as mentioned above. The slow antenna electric field change data for each of 23 flashes (a typical one is shown in Figure 11) reveal no continuing current; perhaps a clue that charge was effectively transferred by the flash from a small volume of charge on the WER/core interface. If this were true, then descent of the WER top would have lowered the height from which the flashes originated. No radar data exist from which WER motions can be determined. Since the flashes were single stroke, a possible test for the height from which the flashes originated might be to determine the stepped leader durations and see if they decreased over the period of interest. Unfortunately, there is no way to determine unambiguously the stepped leader times (Beasley, et al., 1982). However, for 19 of the flashes we believe a reasonable estimate of the leader duration could be made from the electric field change data. Figure 17 shows a graph of the estimated stepped leader times versus CST over the interval corresponding to the first peak in the CG lightning rate. There appears to be a decrease in stepped leader times over the period from 1755 - 1820 CST. In this period the CG lightning rate went through a peak, the radar reflectivity increased, the cloud top decreased, there was a radar reflectivity spike, there was a hook echo, and the wall cloud features showed evidence of updraft loading. At the end of the interval the IC rate increased. Again, we think these events might indicate that the flashes originated from the WER/core boundary as the WER descended.

The IC:CG ratio shown in Figure 9 is difficult to fit into a conceptual framework. Our visual sighting of lightning in the clouds is obviously limited. IC lightning is very frequent in the decaying stages of thunderstorms, i.e. after the updraft has been throttled. The storm top collapsed at a time slightly later than the observed increase in the IC:CG ratio. Perhaps the collapsing cloud lowers charge which increases the chance of IC lightning.

In earlier work (Rust, et al., 1981a), we reported that positive CG flashes are often observed in supercell thunderstorms. Out of 798 flashes identified as cloud-to-ground in the 19 June 1980 storm, only two were positive. Undoubtedly, other positive flashes did occur, but they were certainly less frequent than we would have expected on the basis of earlier observations. The principal difference between this storm and others we have studied was that is was an extreme right-mover, i.e. the storm track was well to the right of any environmental winds.

E2. Electric Fields

As a final comment on our electrical measurements from the mobile lab, we point out that we observed a significant increase in the electric field (Figure 12) when we were in a position near the wall cloud (1823 CST). As the edge of the wall cloud moved nearer to us, the electric field increased abruptly from 2 kV/m to 23 kV/m (at about the time the cloud top collapsed). The change might have been produced in one or more ways; four come to mind. First, a corona layer at the ground could have been swept away by the strong updrafting winds. As a consequence negative charge overhead was exposed. Second, the cloud's negative charge center could have been lowered by some process within the cloud. Third, the cloud's positive charge could have diminished, perhaps by a screening layer of negative charge lowered as the cloud top collapsed. Finally, an increase in the rate of charge generation and separation might have produced an increase in the total negative electric charge overhead. The electric field record in Figure 12 is complicated. Note that at the time the electric field increased (approximately 1823 CST), the CG lightning rate was at a minimum and the IC:CG rate was a maximum. The abrupt increase in electric field almost coincides with both the times of the peak in IC:CG ratio and the collapsing cloud top. The fact that the direction of the change in the electric field indicates more negative charge overhead leads us to suspect that negative charge was lowered as the cloud top collapsed.

F. CONCLUSIONS AND FINAL REMARKS

Observations made while tracking severe convective storms make it possible to interpret visual cloud features in terms of storm structure. Use of cloud features to infer either dynamics or correlations between electrical and dynamical properties is qualitative. But there is little doubt that cloud features indicative of storm development can be identified.

The data for the 19 June 1980 isolated supercell indicate that the main updraft is very important in both the electrification of the storm and in its electrical history. Each time there was any evidence that the updraft might have weakened, then a preceding decrease in the CG rate preceded the weakening. Our impression is that the magnitude of the flash-to-ground rate during a storm's mature stage is probably determined by the mechanism by which the updraft is throttled, but probably not the temporal variations.

Speculations about possible correlations between storm electricity and dynamics provides some insight into the direction of continued study of severe storms, but in the absence of results from specific experiments designed to test particular aspects of co-evolving dynamics and electricity, the electrical character of these enormously large thunderstorms will remain within the realm of speculation. A beauty of the mobile laboratory is that experiments can be conducted from within a region of a storm of particular interest. We are planning future experiments (both on the ground and aloft) to be performed within the storm updraft region. Which we believe to be the major region of importance in electrification of supercell thunderstorms.

G. FIGURE CAPTIONS

Figure 1. Three views of a typical severe convective storm: a). a distant view; b). a horizontal cross-sectional view (the dashed circular region indicates where CG lightning is most frequently observed); c). a view from within the surface inflow region. An * marks the mobile laboratory's tracking position. Most frequently the storms track to the NE; the 19 June 1980 storm track was to the SE.

Figure 2. Summary weather map for 1800 CST on 19 June 1980. Frontal position (standard symbols), 21 C dewpoint temperatures (shaded), and wind directions (broad arrows) are all at the surface. Wind barbs (long barb is 5 m/s) and shortwave trough position' (dashed line) are from 500 mb. Storm location is at X.

Figure 3. Photograph of the wall cloud at 1821 CST on 19 June 1980.

Figure 4. Data recording equipment in the mobile laboratory.

Figure 5. Storm track with dots at 30 min. intervals. Indications of severe weather are: hail (H); severe hailswath (shaded); a funnel cloud (F); and a tornado (T). The mobile lab positions from 1749-2000 CST are marked as a line of x's. Mean wind vector from 1800 CST Amarillo, TX (AMA) rawinsonde is shown.

Figure 6. Traces of storm top (top) and low level radar reflectivity maxima (bottom) versus time. Merger of the main storm cell with two less significant echoes on the PPI display are indicated.

Figure 7. Radial divergence near storm top and cyclonic shear at mid levels observed with NSSL's Doppler radar at Norman, OK.

Figure 8. (a). Flash rates determined from electric field changes, visual documentation, and TV; and (b). combined WSR-57 and Doppler radar data.

Figure 9. The CG flash rate determined both visually and from electric field changes, and the IC:CG ratio estimated from the electric field changes.

Figure 10. Ratio of single stroke to multiple stroke CG flashes.

Figure 11. Field change record for a typical single stroke CG flash determined with a 10 s antenna.

Figure 12. Electric field measured beneath the wall cloud. The values have been corrected for distortion of the field by the mobile lab.

Figure 13. Updraft/downdraft couplet in a supercell thunderstorm. The shaded area represents a typical 40 dBZ contour.

Figure 14. Wall cloud with smooth and laminar rotation. The photograph was taken near Ringling, OK at 1615 CST during the spring of 1976.

Figure 15. The same wall cloud shown in Figure 11 with a ruffled appearance. The photograph was taken at 1625 CST.

Figure 16. The same wall cloud shown in Figures 14 and 15 but showing a decreased radius of maximum tangential velocity. The photograph was taken at 1645 CST.

Figure 17. Stepped leader duration as a function of time. Shaded region shows total CG flashes per 5 min intervals. Straight line represents typical descent rate of WER.

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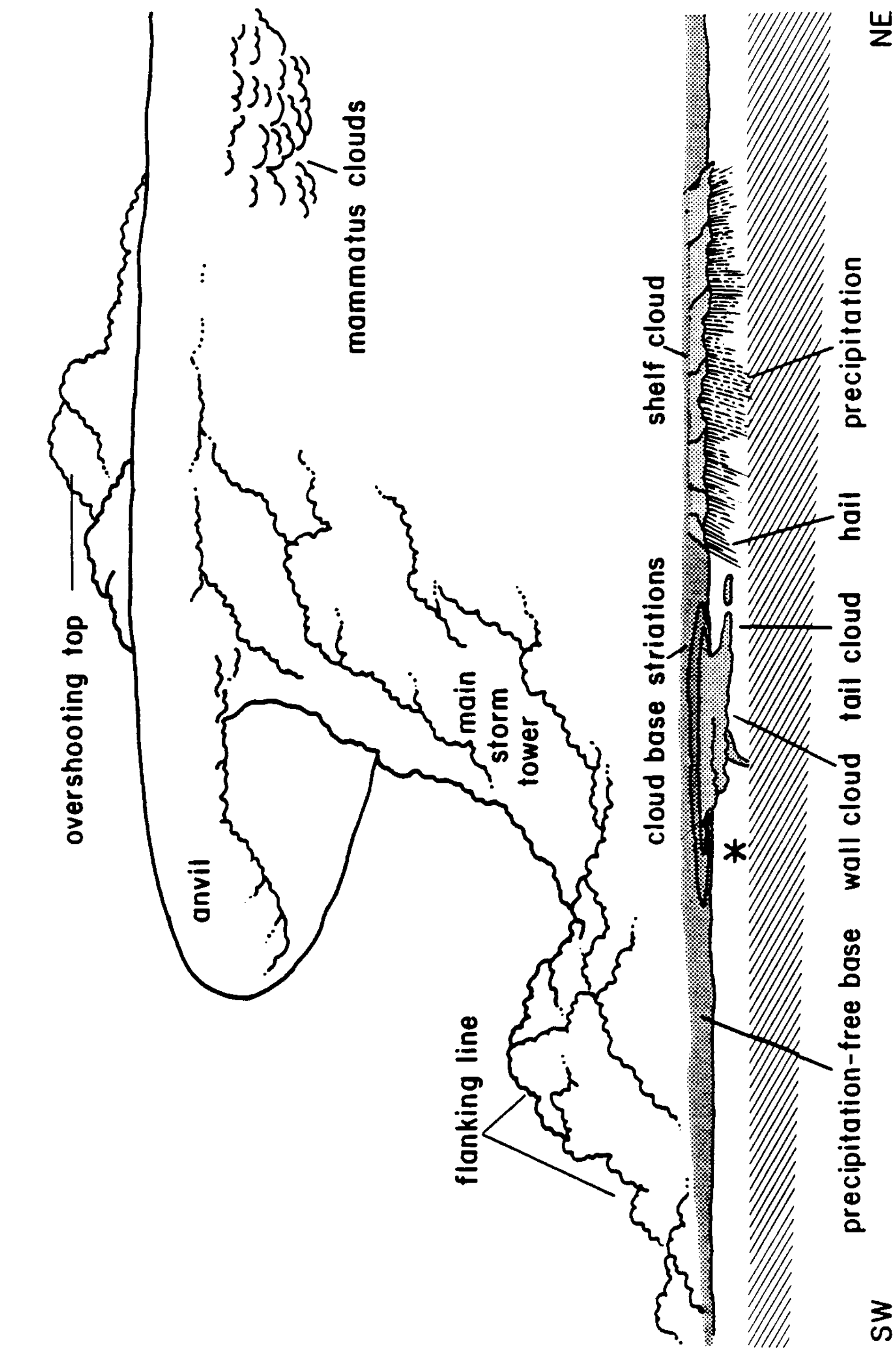

overshooting top
anvil
mammatus clouds
main storm tower
flanking line
shelf cloud
cloud base striations
precipitation
hail
tail cloud
wall cloud
*
precipitation-free base
SW
NE

Fig. 1a

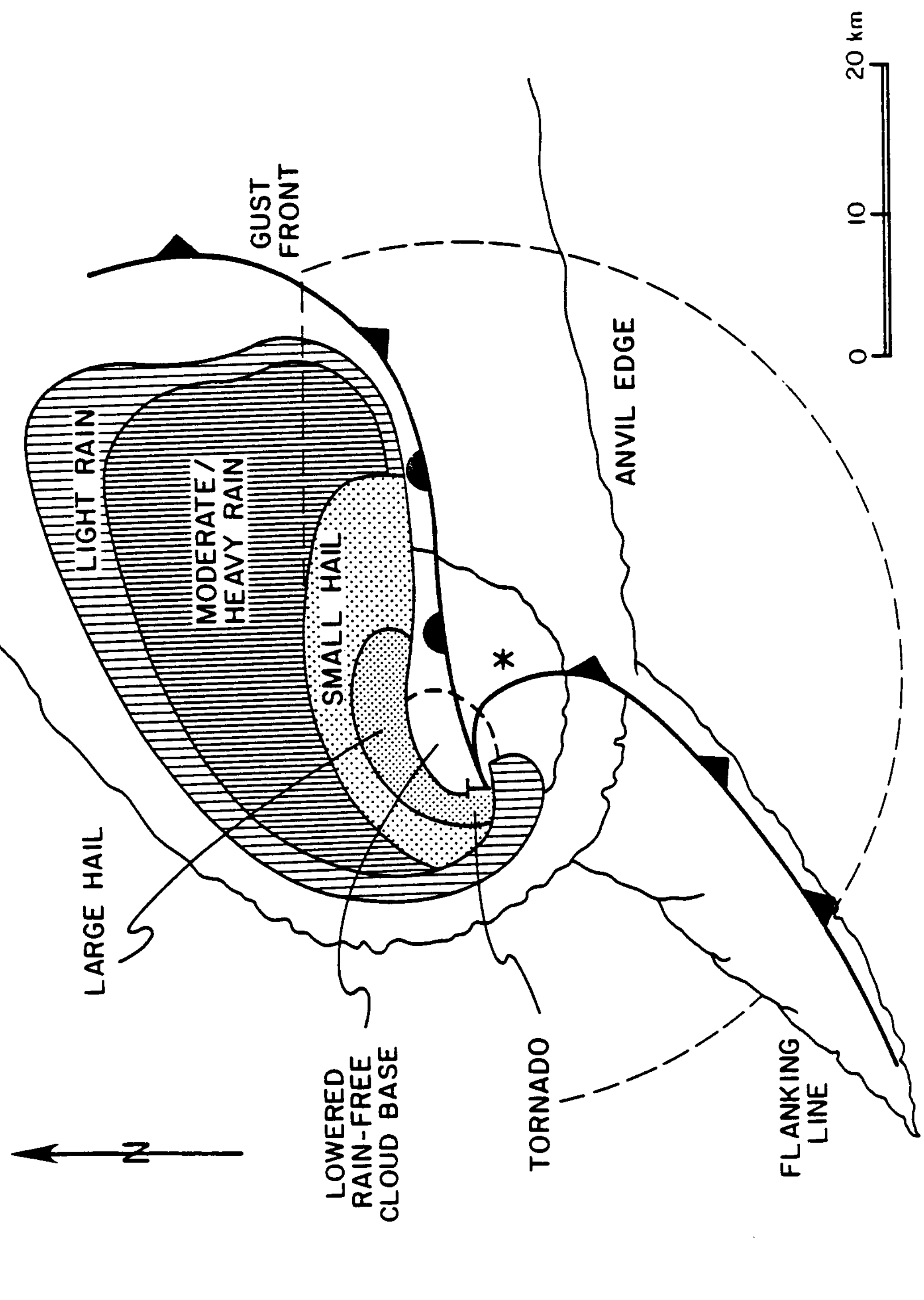

GUST FRONT
LIGHT RAIN
MODERATE/ HEAVY RAIN
SMALL HAIL
ANVIL EDGE
LARGE HAIL
LOWERED RAIN-FREE CLOUD BASE
TORNADO
FLANKING LINE
N
0
10
20 km

Fig. 1b

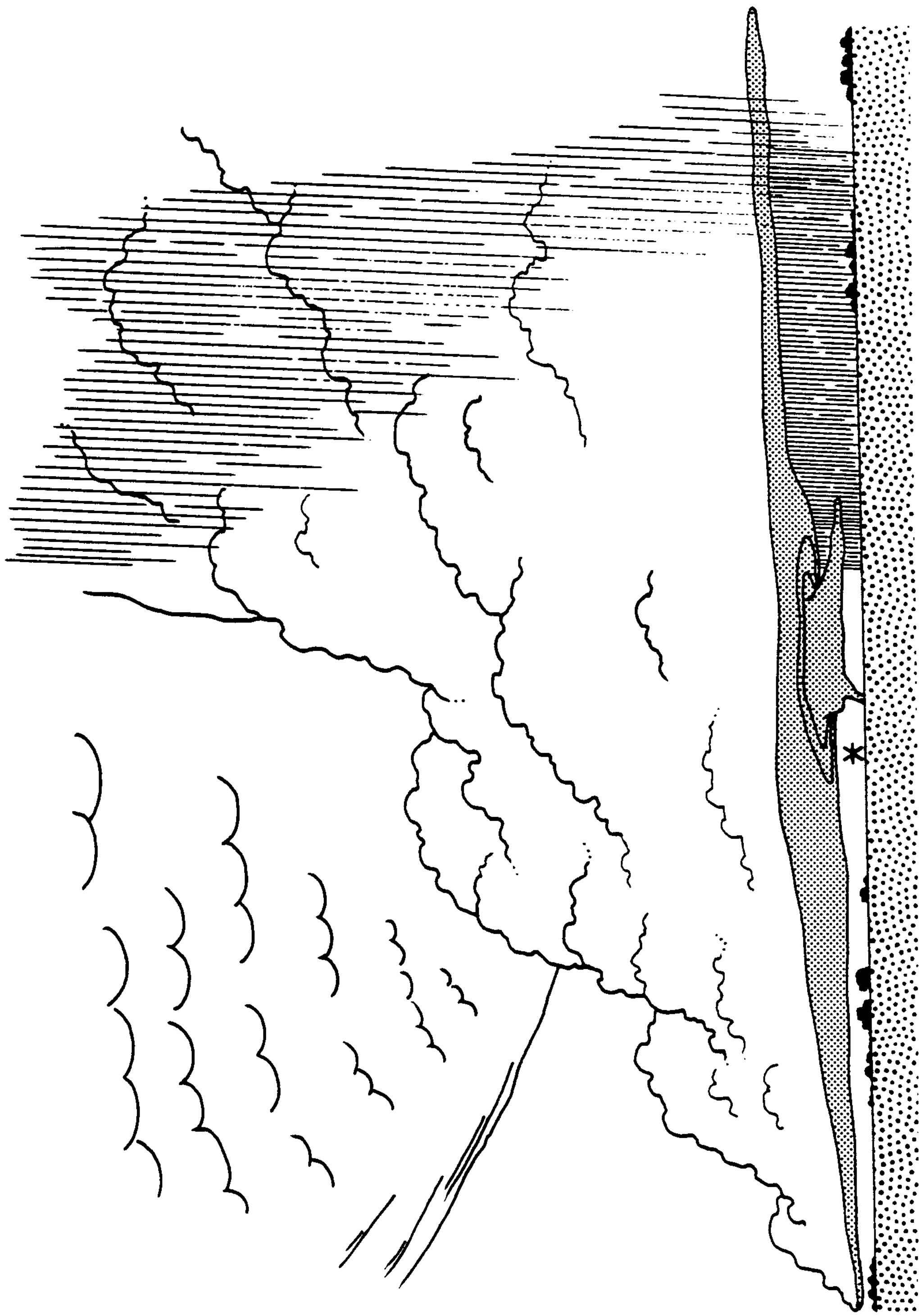


Fig. 1c

1800 CST 19 JUNE 81

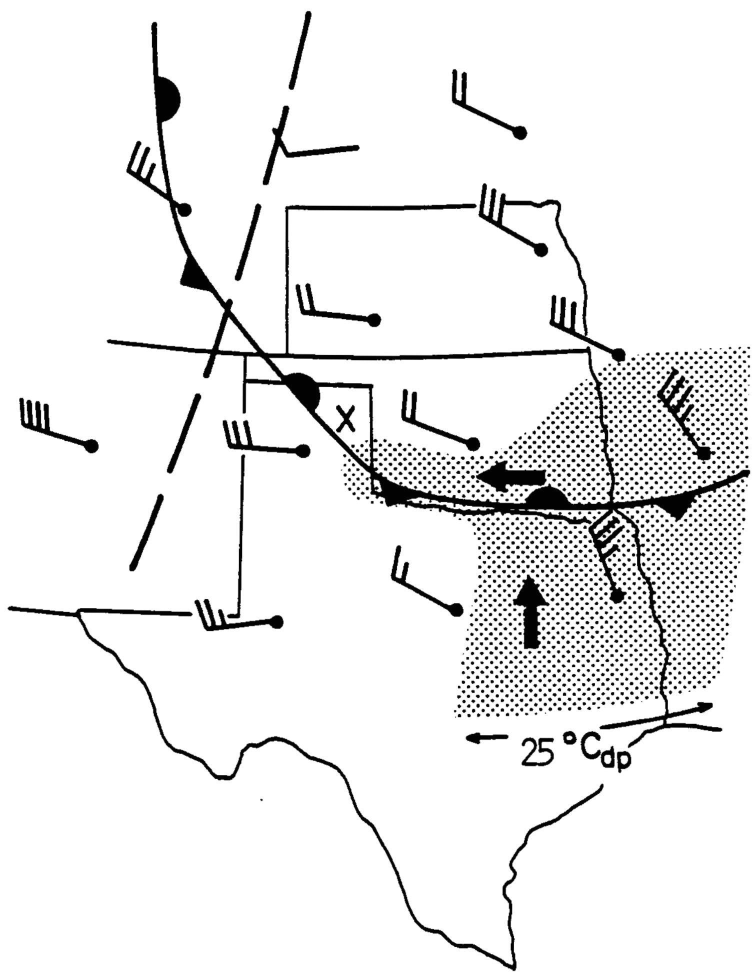


Fig. 2

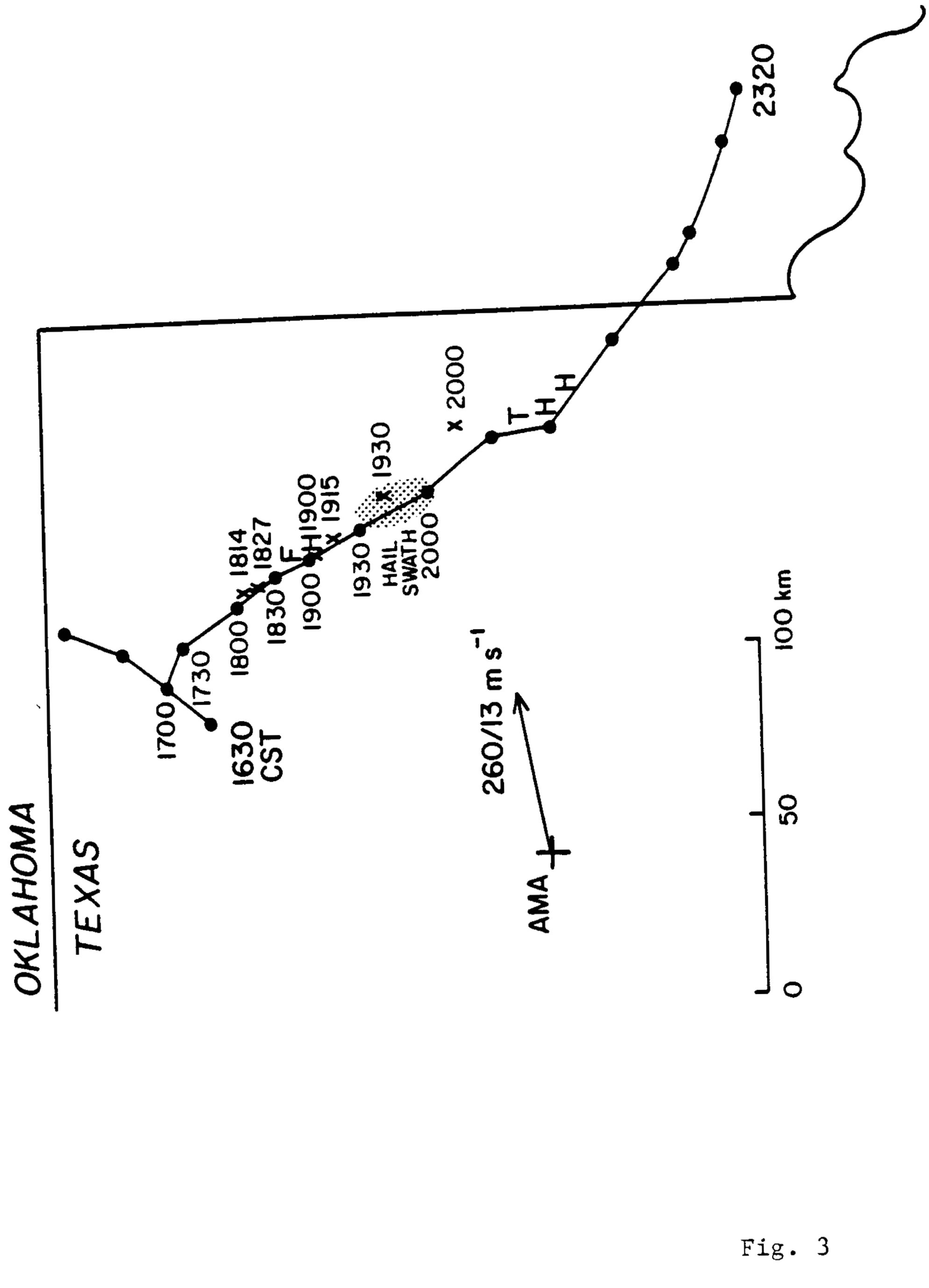
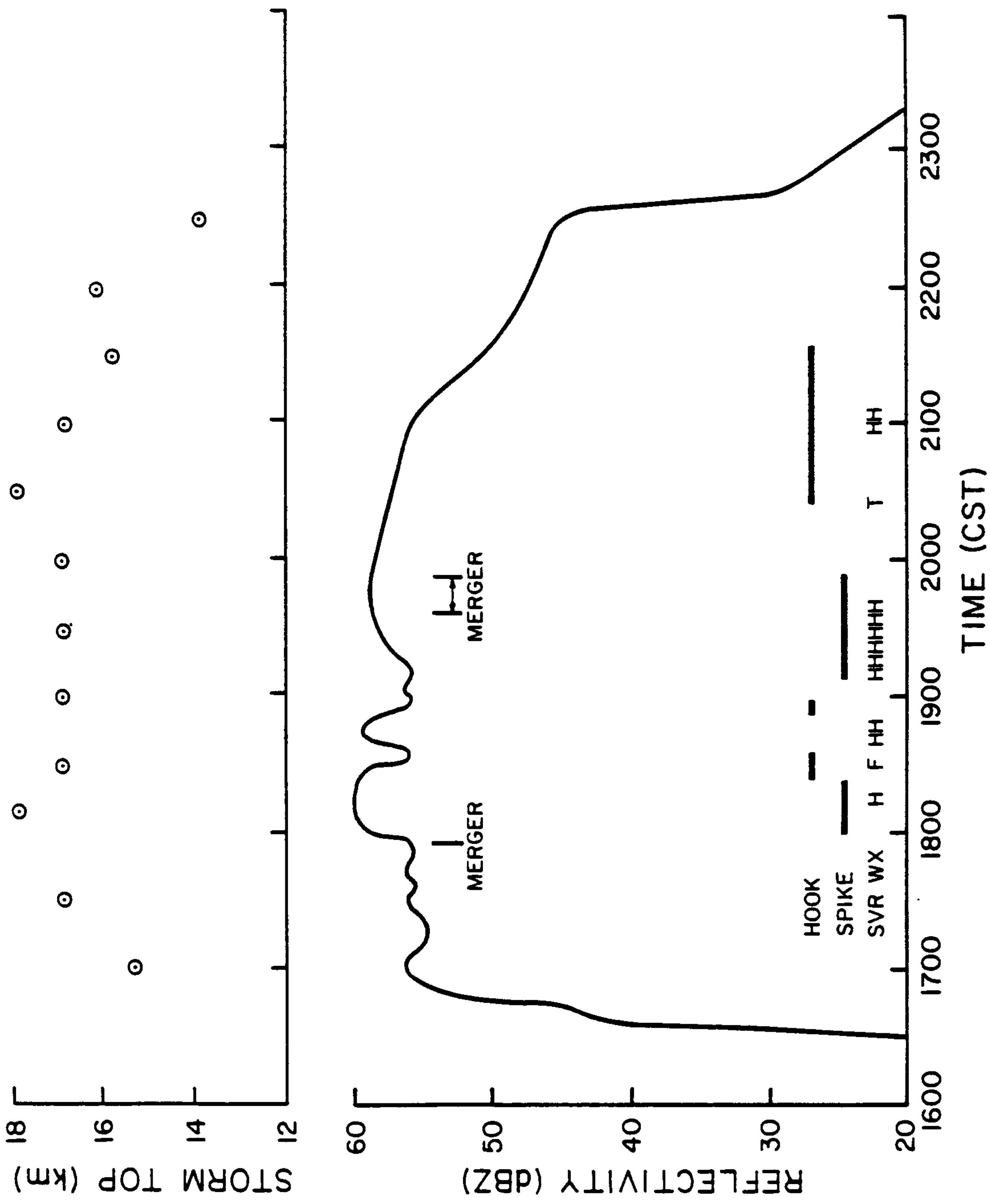

OKLAHOMA
TEXAS
1630 CST
1700
1730
1800
1814
1827
1830
F
H
1900
1900
1915
1930
1930
HAIL SWATH
2000
2000
T
H
H
2320
260/13 m s^{-1}
AMA
0
50
100 km

Fig. 3



STORM TOP (km)
18
16
14
12
REFLECTIVITY (dBZ)
60
50
40
30
20
MERGER
MERGER
HOOK
SPIKE
SVR WX
H
F
T
1600
1700
1800
1900
2000
2100
2200
2300
TIME (CST)

Fig. 4

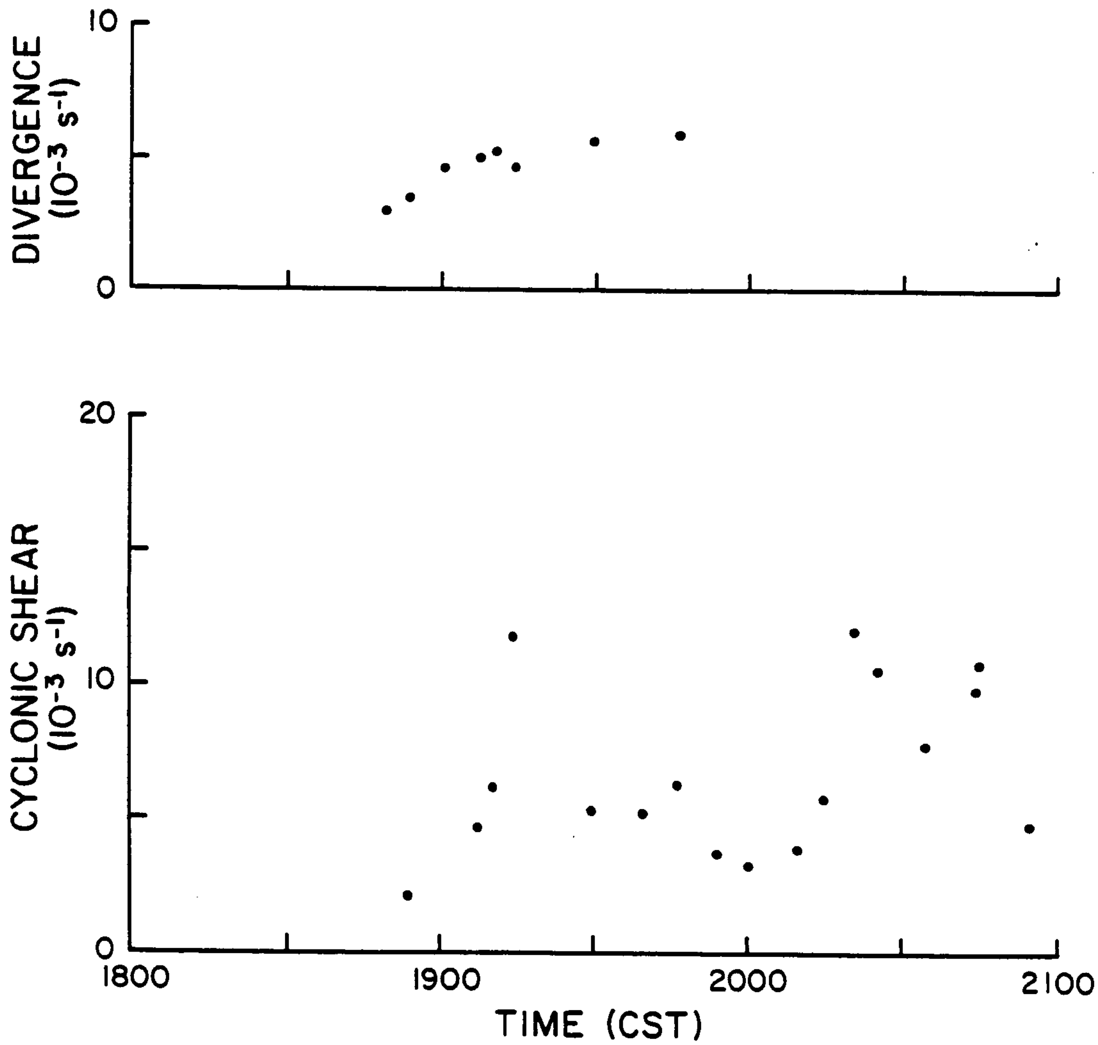

10
DIVERGENCE
(10-3 s-1)
0
20
CYCLONIC SHEAR
(10-3 s-1)
10
0
1800
1900
2000
2100
TIME (CST)

Fig. 5

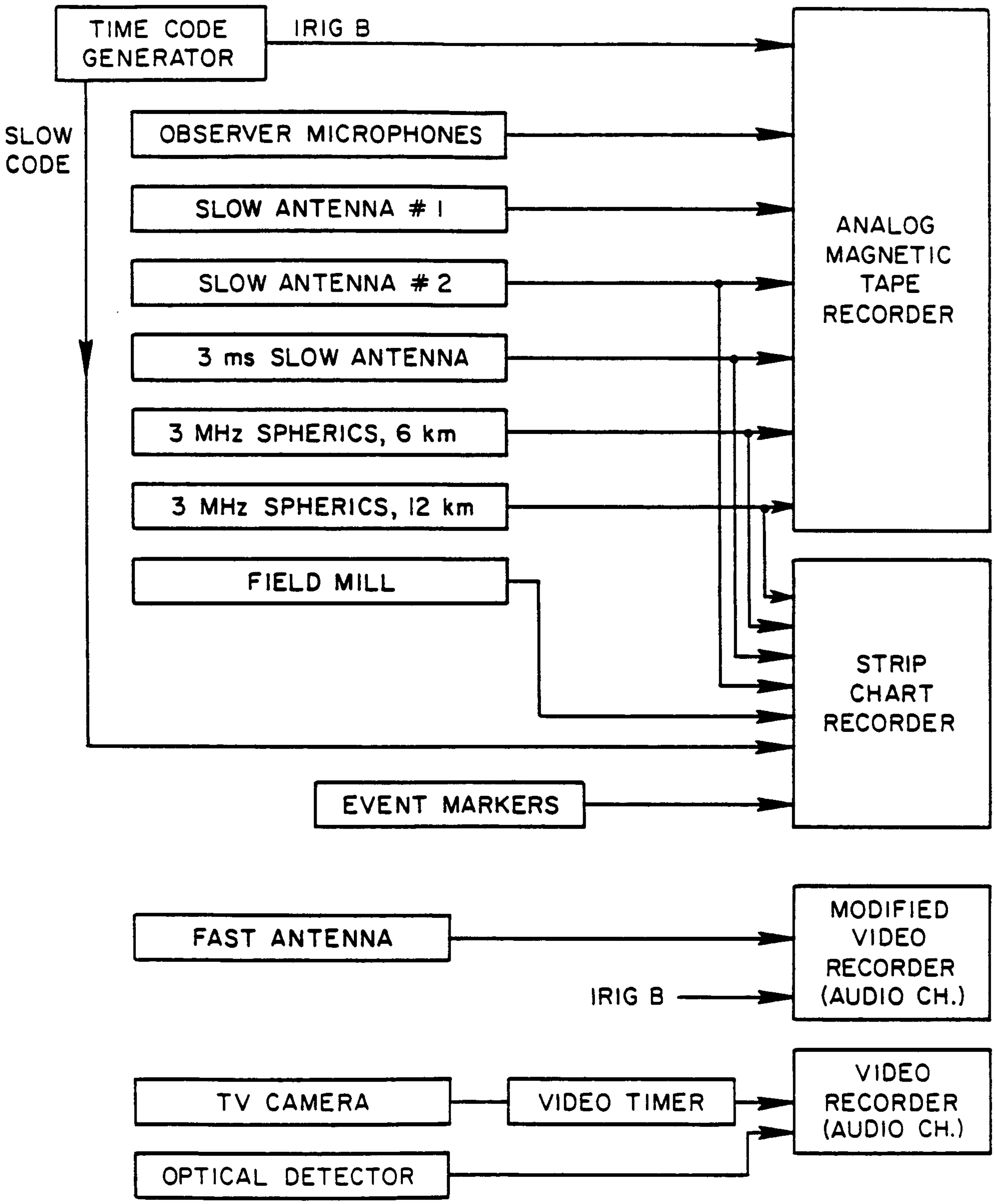


Fig. 7

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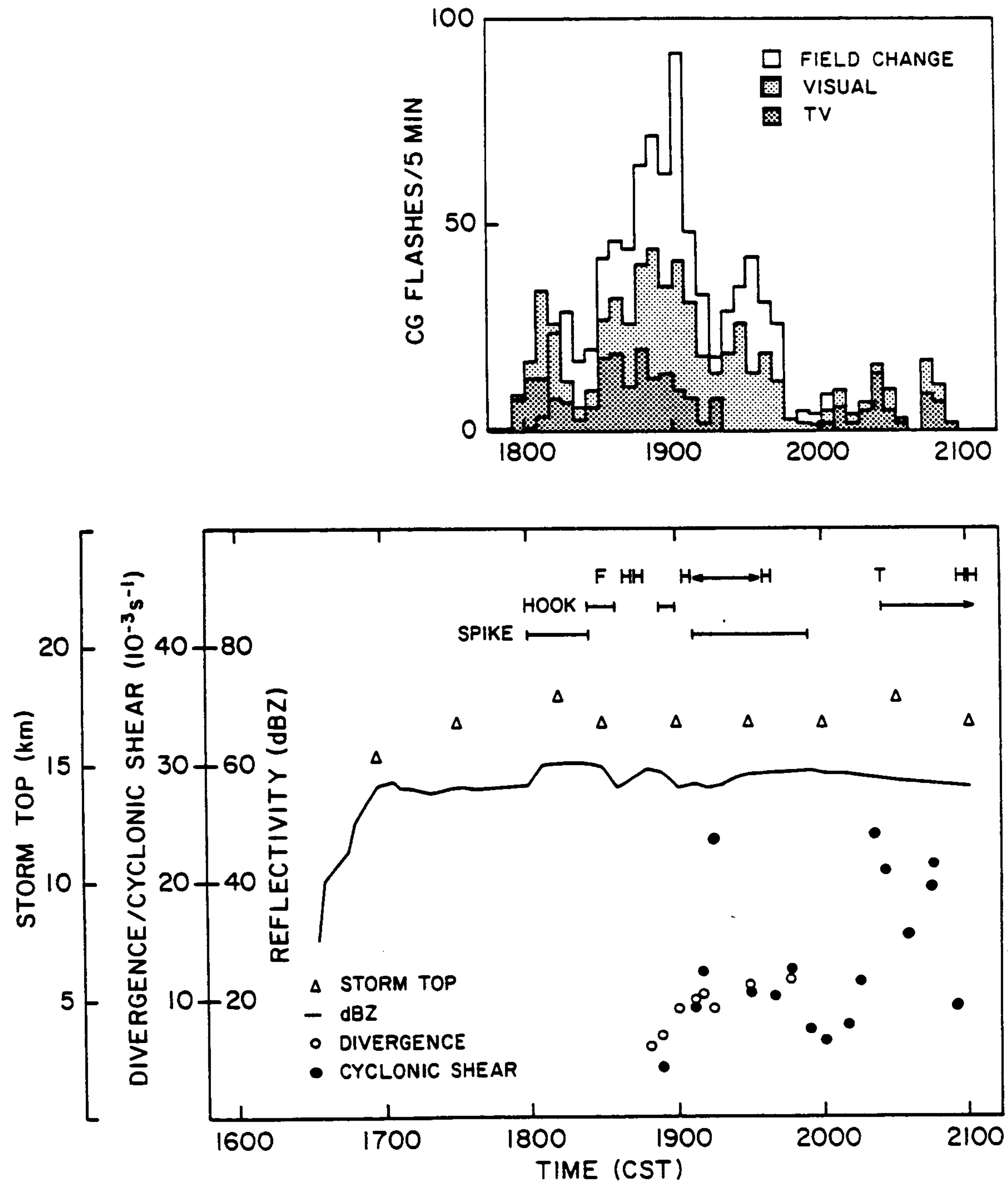

CG FLASHES/5 MIN
FIELD CHANGE
VISUAL
TV
100
50
0
1800
1900
2000
2100
STORM TOP (km)
DIVERGENCE/CYCLONIC SHEAR ($10^{-3}s^{-1}$)
REFLECTIVITY (dBZ)
F HH
H H
T HH
HOOK
SPIKE
STORM TOP
dBZ
DIVERGENCE
CYCLONIC SHEAR
TIME (CST)
1600
1700
1800
1900
2000
2100

Fig. 8

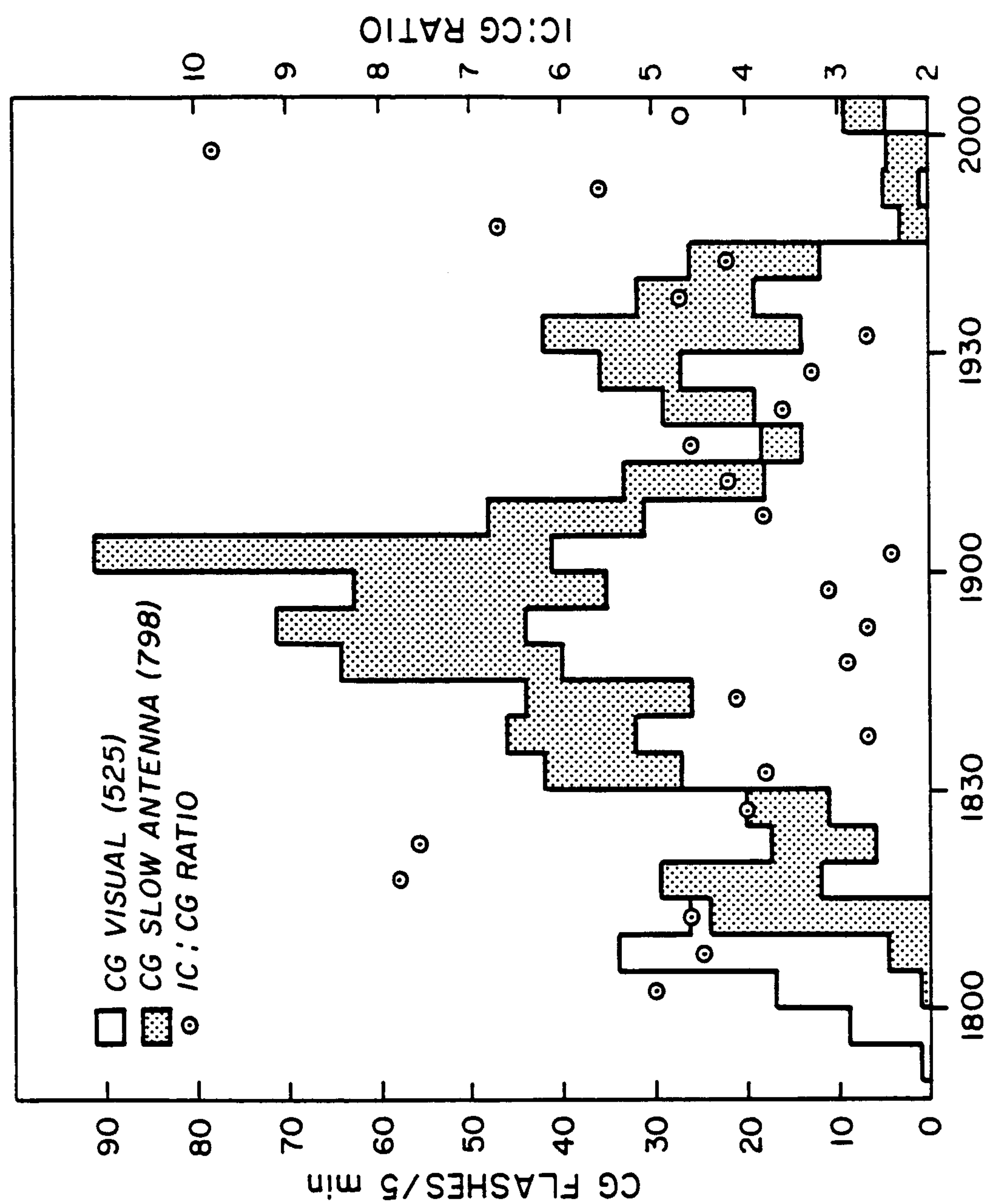
CG VISUAL (525)
CG SLOW ANTENNA (798)
IC : CG RATIO
CG FLASHES/5 min
IC:CG RATIO
0
10
20
30
40
50
60
70
80
90
2
3
4
5
6
7
8
9
10
1800
1830
1900
1930
2000

Fig. 9

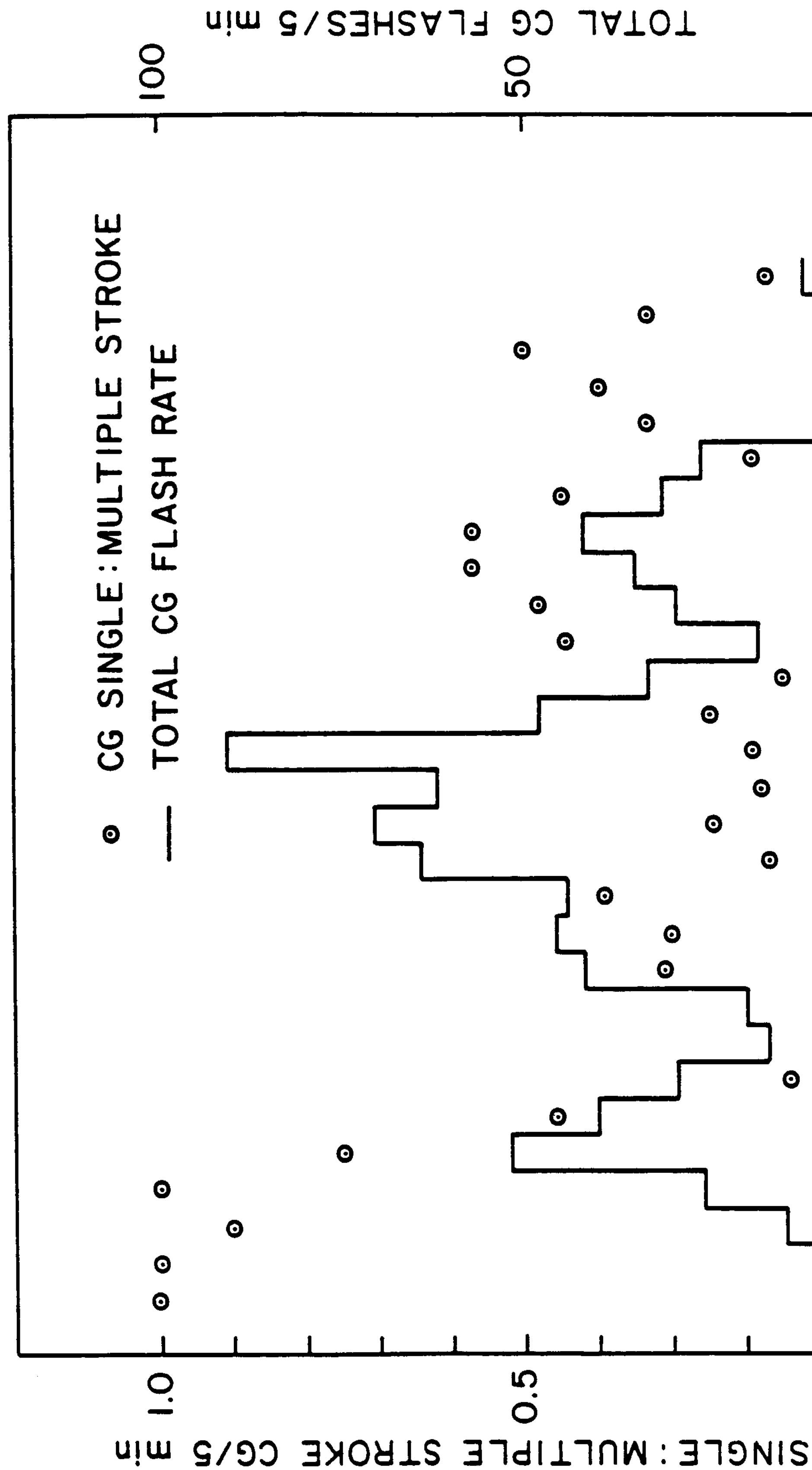
CG SINGLE : MULTIPLE STROKE
TOTAL CG FLASH RATE
TOTAL CG FLASHES/5 min
SINGLE : MULTIPLE STROKE CG/5 min
100
50
0
1.0
0.5
0
1800
1830
1900
1930
2000

Fig. 10

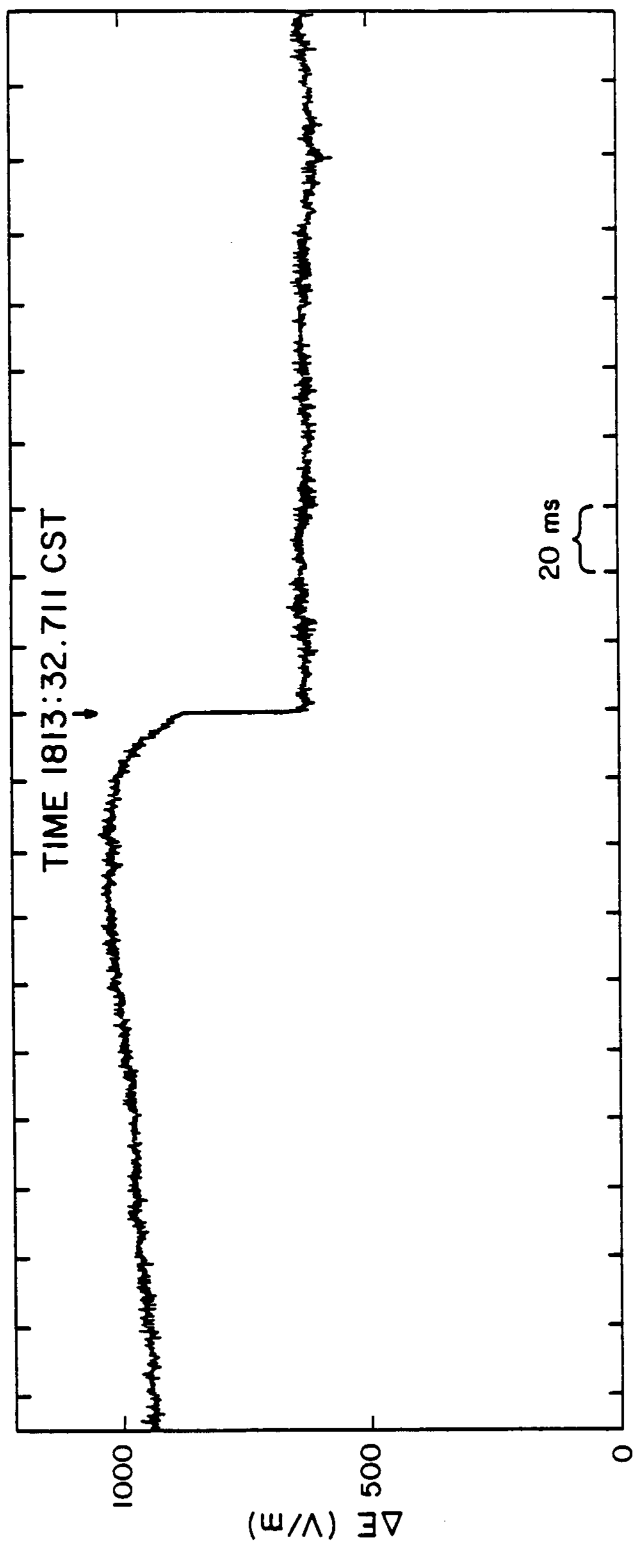

Fig. 11

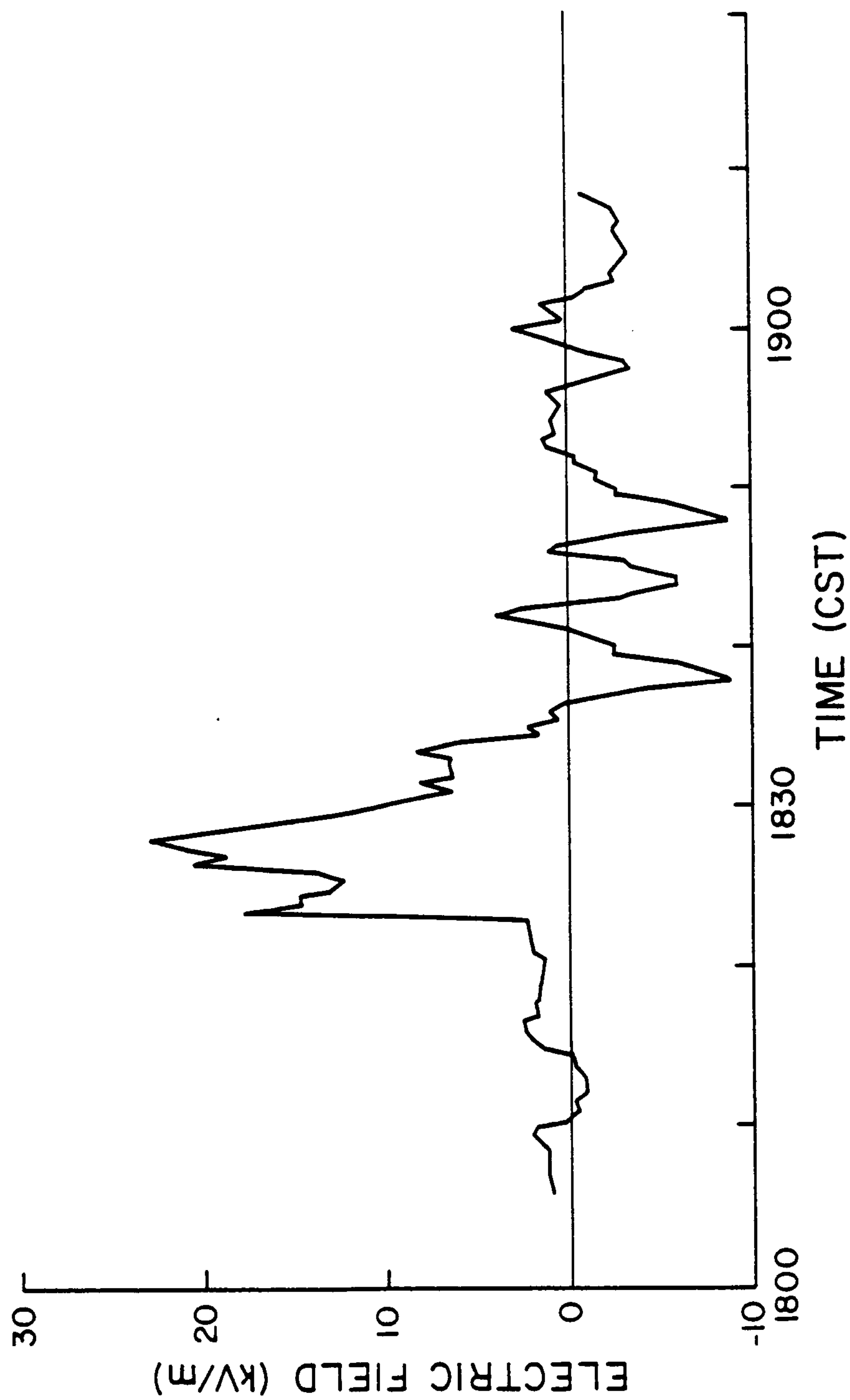

Fig. 12

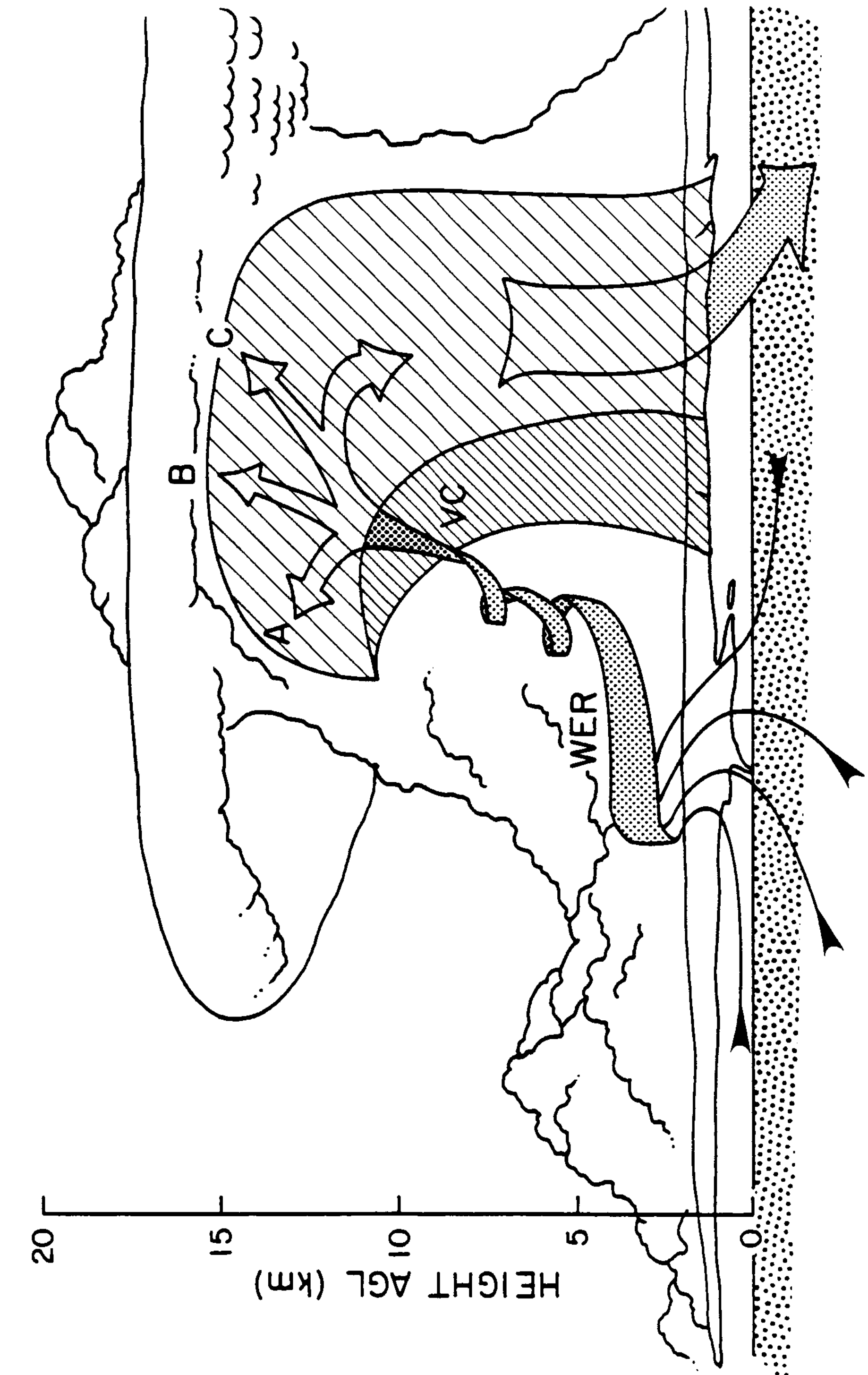

Fig. 13

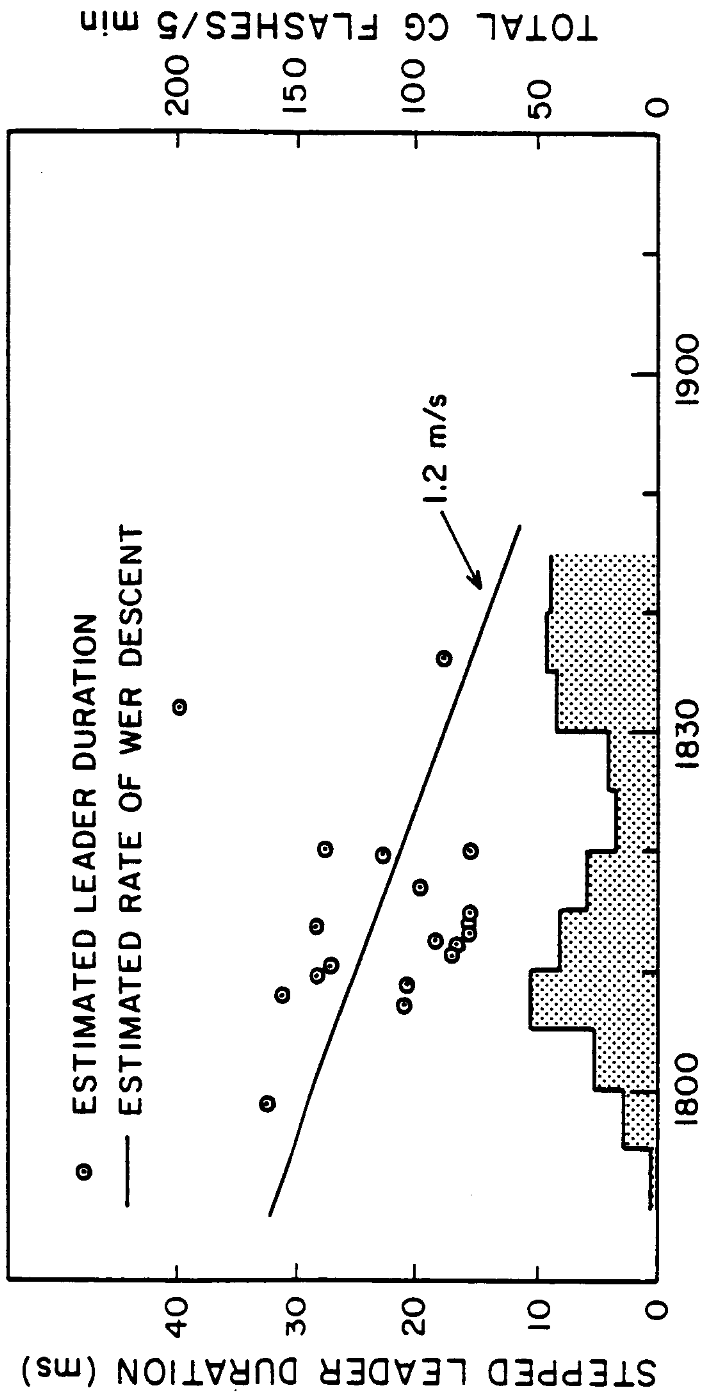

Fig. 17

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14 - 16