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OBSERVATIONS OF WATERSPOUTS AND THEIR PARENT CLOUDS

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16. Abstract

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Of the 104 events sighted, it was found that 30 rotated cyclonically, 9 anticyclonically, and the rest either went unnoticed or were not observable. The parent clouds had tops at 8,000-12,000 ft and bottoms from 800-2,500 ft altitude. Other results obtained on the characteristics of waterspouts supplement those in past publications but still do not appear to disclose the mechanism responsible for the formation of the vortex at the time and location of its occurrence. The relationship of these results to tornado structure is uncertain.

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PREFACE

A large number of individuals participated in this project. Particular acknowledgment is due Prof. Harold P. Gerrish of the University of Miami for suggesting the region around southern Florida as the area for research and for his advice and consultations during the study, and to Mr. James Hughes of the Office of Naval Research, Washington, D. C., and Cdr. R. V. Wilson who suggested that the research be made a Navy Fleet Research Investigation and then assisted in bringing about the necessary arrangements. The electric field measuring equipment was designed and built under the direction of Dr. Joe Nanevicz of the Electromagnetic Sciences Laboratory at Stanford Research Institute. The gear was installed by Grumman Aircraft Engineering Corp. who aided Navy personnel in keeping the MAD gear highly tuned so that magnetic anomalies could be readily identified. Finally, special thanks are given to members of the Shipping Surveillance Patrol for the data obtained gratis during 1967 and to the personnel of Air Development Squadron 1 at Key West Naval Air Station. Particular thanks are due Cdrs. R. V. Wilson and N. P. Carr and Lt. J. F. Fitzgerald of VX-1 and Lcdr. D. R. Simon of Shipping Surveillance Patrol for the diligence, persistence, and care taken to obtain the data on waterspouts. Support and services given at no cost to the project by personnel of the 7th Coast Guard District and of the Cutters DILIGENCE, ACTIVE, and ARIADNE are also gratefully acknowledged.

OBSERVATIONS OF WATERSPOUTS AND THEIR PARENT CLOUDS

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SUMMARY

Results of a study of waterspouts during the summers of 1967 and 1968 in the area around Key West, Florida are presented. Observations were made from Coast Guard Cutters and from aircraft assigned to the Key West Naval Air Station on a cooperative basis with NASA, Ames Research Center. Measurements made of the electric and magnetic fields associated with these atmospheric vortices indicate that electricity does not play a primary role in their structure and could be eliminated as a generating mechanism or as a means of identification. The measurements did not clarify a secondary or augmentation role for electrical energy because the events which involved electrical activity could not be studied thoroughly enough to identify the relationship with the vortex. Although electricity is eliminated as an essential or defining mechanism, some evidence was found (low cloud tops and a lightning demise of a spout) to indicate that these vortices cannot exist if electricity is too prominent.

Of the 104 events sighted, it was found that 30 rotated cyclonically, 9 anticyclonically, and the rest either went unnoticed or were not observable. The parent clouds had tops at 8,000-12,000 ft and bottoms from 800-2,500 ft altitude. Other results obtained on the characteristics of waterspouts supplement those in past publications but still do not appear to disclose the mechanism responsible for the formation of the vortex at the time and location of its occurrence. The relationship of these results to tornado structure is uncertain.

INTRODUCTION

The fact that only one of several seemingly identical clouds will spawn a funnel has led to much speculation as to what features of the environment initiate or support the atmospheric vortex of a tornado or waterspout event. Since a vortex requires a volume of fluid with reasonably well-organized angular momentum and a pump mechanism for removal of fluid at a point near the center of rotation of the mass of air, a satisfactory explanation should account for both of these basic items. One of the early choices for the responsible mechanism was electricity (e.g., refs. 1 and 2), probably because of its association with the funnel and with the severe weather and because of the unknown character and capability of electricity. At about the same time, Espy (ref. 3) and others studied the role of water condensation and evaporation in driving a tornado vortex. More recent calculations by Fulks (ref. 4) and Vonnegut (ref. 5) indicate that for the model assumed, buoyancy of an air column brought about by temperature differences in the air and by condensation of water vapor is not enough to account for the 200-500 mph velocities believed to be associated with severe tornadoes. Calculations such as these and the observations of electrical phenomena in and near tornado funnels, such as those reported in references 5-12, revived the idea that electrical heating or forces might play a critical role in tornado dynamics. The electric current and magnetic data of Boucher reported recently by Brook[1] (ref. 13) for a tornado in Oklahoma also encouraged the association of tornadoes with electricity.

Means whereby electricity might be coupled into the vortex have been studied theoretically and experimentally in the laboratory for a number of models. Vonnegut (ref. 5) summarized the various ideas expressed in the literature prior to 1960 and studied several electrical models. Since that time various electrical mechanisms have been proposed and investigated (refs. 14-20), some of which are extensions or modifications of prior studies. Brief descriptions of typical electrical theories are presented in appendix A together with an estimate for the variation of the magnetic- and electric-field signals to be anticipated as a function of the diameter of the funnel. Results of these calculations and a few data points are presented and discussed. Although a unique solution is not assured for a single process, data falling along a given curve would indicate that electricity is a consistent part of the vortex structure, and the functional variation would tend to support certain theories and reject others. Also, if both electric and magnetic fields were known, it should in some cases be possible to determine if the vortex is generating or receiving electrical power. In addition to making measurements such as these, Silberg proposed dropping short wires from an aircraft to reduce electric fields over and around the vortex in a manner employed by Kasemir and Weickmann (ref. 20). Rossow (ref. 18) proposed deploying long wires through the cloud from gun- or rocket-launched bobbins to trigger lightning as has been done by Newman and his associates (ref. 21) for nonvortex clouds.

On the basis of the foregoing theories, laboratory experiments, and data, a systematic program was undertaken at Ames Research Center to obtain measurements of the electric and magnetic fields near atmospheric vortices, such as tornadoes and waterspouts, and their parent clouds and to launch long wires into and through the clouds over the vortices. The objective of the measurements was to determine whether electric and magnetic fields are a consistent part of these events and, if so, the orientation and location of such fields relative to the funnel. In this way it should be possible to find out whether the electricity results from or contributes to the energy of the vortex. (Since an opportunity to launch wires into a waterspout cloud was not found, that part of the study will not be discussed further.) Reports on studies of tornadoes in the midwestern United States (e.g., refs. 4, 22-31) reveal that tornadoes occur quite frequently but over an area so large and in a manner so unpredictable that the possibility of observing a significant number of events in a given year is remote. Prof. Harold P. Gerrish of the University of Miami suggested to the author the region around southern Florida as promising for research on waterspouts because of their frequency

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[1]The late E. H. Vestine suggested that the magnetic field variation measured by Boucher might be attributed to a solar magnetic disturbance that occurred at about that time. Closer examination by Richard E. Orville of State University of New York at Albany showed that the magnitude of the solar disturbance could account for only a part of the signal; it is therefore still felt that the major portion must have been generated locally.

of occurrence in that area and because permission to attempt modification could more easily be obtained for events over water than for those over land. Papers on waterspouts (e.g., refs. 30-36) showed the months of June through September to be most active with a fringe period of increase in May and decrease in October.

The U. S. Navy and Coast Guard facilities around southern Florida and in the Gulf of Mexico were contacted regarding the possibility of observing waterspouts to make measurements on them and to try the wire-deploying device on a parent cloud. The availability of magnetic-anomaly-detection equipment (MAD gear) installed on Navy aircraft (P2V and S2 series) as an operating system made possible airborne measurements of the magnetic fields (i.e., electric currents) in the vicinity of waterspouts without the procurement, development, or modification of equipment. Therefore, early in 1967 Mr. James Hughes of the Atmospheric Sciences Branch of the Office of Naval Research arranged to have aircraft of the Shipping Surveillance Patrol at the Key West Naval Air Station make measurements on waterspouts observed while on patrol. These patrols, under the supervision of Lcdr. Donald R. Simon, obtained data on nine events during 1967 (see table 1). Arrangements were also made by Mr. Hughes so that the author and Harold Clements of Ames could accompany Coast Guard crews on patrol in the Cay Sal area between the Florida Keys, Cuba, and the Bahamas to observe waterspouts and to fire wire-deploying projectiles into the cloud over any waterspout within range. Sixteen waterspouts were seen (see table 1) during 5 weeks on board the cutters DILIGENCE, ARIADNE, and ACTIVE, but none were within range of the wire-deploying projectiles.

Measurements were made during 1968 with both electrometers and a magnetometer from a Grumman S2E aircraft assigned to the project. At the suggestion of Cdr. Richard V. Wilson of the Air Development Squadron 1 (VX-1) at NAS Key West the project was made a Fleet Research Investigation (F/R 107) of the Navy so that the study could be made on a regular rather than a convenience basis. Daily flights from 8 June through 30 September 1968, resulted in the study of 52 waterspouts with the aircraft (see table 1). An additional 27 events were sighted by the author from the ground and these are also listed in table 1 to indicate how often waterspouts are seen in the Key West area and to present certain characteristics that were noted. Based on observations of other people, it is estimated that at least another 100 waterspouts occurred during the summer of 1968 that are not listed in the table. Distribution in size, occurrence, location, etc., agrees with the data gathered by Gerrish (ref. 34).

The present paper presents the results of the 104 observations on waterspouts made during 1967 and 1968 from Coast Guard Cutters, from Navy aircraft, and by the author from the surface. Included is a description of the equipment, of the operating procedures used in the airborne tests, and of the observations made on the funnels and the parent clouds.

EQUIPMENT DESCRIPTION AND TEST PROCEDURES

Figure 1 is a photograph of the Grumman S2E aircraft used for the 1968 study showing the locations of the four electrometer sensors on board and the

AN/ASQ-10 Magnetic-Anomaly-Detector (MAD) head in its retracted position (it is a saturable-core or flux-gate magnetometer). The aircraft is built with the MAD as a standard part of its equipment. The detector was specially designed for a low magnetic noise level; its full-scale ranges of 1, 2.5, 5, 10, 25, and 50 γ ($1\gamma = 10^{-5}$ gauss or 1 nanotesla) provided a maximum sensitivity of 0.02γ. When the equipment was in top operating condition and the aircraft was out over deep water the noise level is about 0.02 to 0.04γ (see fig. 2). A bandpass filter (0.075 to 0.75 cps) is used to eliminate the slow variations in the earth's magnetic field with distance and altitude. Rapid changes in altitude such as those due to gusts and updrafts cause a magnetic anomaly to appear on the tape because of the $0.8\gamma/100$ ft variation with altitude of the earth's magnetic field. Flight procedures required that the pilot notify the operator at the recorder whenever an altitude change occurred since the data runs were being made around a funnel. If one pass out of four yielded a signal and the others did not, it was usually assumed that the anomaly was due to an unobserved altitude change provided the profile resembled others obtained in that way.

The electrometer sensors, control box, amplifiers, etc. (see fig. 3) were designed and built by Dr. Joe Nanevicz and Richard Hilbers of the Electromagnetic Sciences Laboratory at Stanford Research Institute and had full-scale ranges of 1, 3, 10, 30, 100, and 300 kV/m. A low noise level in the equipment (same graphical readout as magnetic detector) permitted the identification of a voltage gradient as low as 20 V/m; for example, the fair weather potential was easily identifiable during ground checks. Although filters limited the time response of the equipment to a range from dc to 10 cps, changes in the electric field when lightning occurred still appeared as nearly discontinuous on the tapes (see fig. 4). Note that a magnetic anomaly representative of the current surge in a stroke also appears on the tape. Although electric surveys were made on clouds and readings were taken during electrical activity, that data will not be treated here.

In order to relate the signals on the sensors to the electric field that would exist if the metal aircraft were not there, the sensor locations were calibrated in the laboratory on a scale model of the aircraft (15 in. wing span) covered with metallic paint. The same model was used to locate the sensors in those places on the aircraft where cross-coupling between lateral, longitudinal, and vertical components was at a minimum and where access plates were available for mounting the sensors. As a result, the nose sensor was mounted in place of the nose taxi light and the wing sensor was located on an access panel on the underside of the left wing (fig. 3). The top and bottom units were fastened to the skin through holes made for that purpose and patched when the sensor was removed. The voltage gradient normal to the metal skin of the aircraft at each sensor location is given by

$$E_N = aE_x + bE_y + cE_z + dV_A$$

The calibration constants to be used in this equation to reduce a set of readings for the three components of the electric field and the charge on the aircraft for the sensor locations used are listed as follows:

	Location			
	a	b	c	d, $(m)^{-1}$
Taxi light in nose	8.18	0.592	-1.13	0.628
Point F bottom fuselage station 284	-.03	0	-1.81	.159
Station F top fuselage station 334	-.0208	0	.696	.078
Wing point D (left) 5 in. aft 42 line station 240.5	.428	1.915	-.758	.171

The constants a, b, and c are dimensionless because E_N, E_x, E_y, and E_z have the same dimensions but d has units of m^{-1} because V_A is the voltage to which the aircraft is charged electrically. The x, y, and z axes are alined, respectively, with the fore and aft, the lateral, and the overhead directions relative to the aircraft. Therefore, during straight and level flight the -z axis and the gravity force are alined. Solving the resulting four simultaneous algebraic equations yields the electric fields. Data from the four electrometers and the magnetometer were recorded on a six-channel paper tape recorder. Rotational motion of the aircraft in an electric field causes signal variations on the sensors, and any abrupt change in g-load causes a signal to be generated in the MAD sensor. Therefore, care was taken during all data runs to keep the aircraft on a straight and level course for a sufficient time (usually 1 min) before and after passing the funnel to reduce the possibility of signals arising from aircraft maneuvers.

Operational procedures and manpower requirements of the Navy limited the flights to one per day Monday through Friday each being 4 to 6 hours duration. About one-half hour was required to get airborne and 15 minutes to shut down the equipment after the wheels touched down. Because a one-day lead time was usually required to schedule a flight, it was not possible to fly on a moment's notice when the weather looked promising. Since the weather is nearly the same in the Key West vicinity from May through September it was not possible to determine in advance which days were promising waterspout days and which were not. Flights scheduled during morning hours were just as successful as those during the afternoon.

The crew usually consisted of a pilot, a copilot, or photographer,[2] a MAD operator, and an operator for the electrometers and recorder (usually the author). Once airborne, the pilot would contact the Navy radar station by radio to inquire where clouds with strong radar returns (i.e., with sizable water content) were located. The ESSA Weather Bureau Office at the Key West International Airport also provided information on likely areas of waterspout activity. Any promising clouds in the local area were first flown under and around. It turned out that the use of information and advice given to us by Professor Harold G. Gerrish (e.g., refs. 32 to 35) of the University of Miami made sightings from the aircraft the most successful way of finding funnel clouds. Detectable radar echoes seemed to follow the occurrence of a

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[2]W. A. Melliar, an Ames photographer, accompanied flights from 15 July to 10 August.

waterspout rather than to precede or accompany it. With experience the pilots and operators on board were able to locate likely clouds visually. As is to be expected, locating funnels with one aircraft resulted in some events being missed and in the study of small funnels while larger ones were later found to have been in progress elsewhere. Various rules of thumb were found to apply quite generally, but eventually all rules laid out were violated by one or more events. In general, if a cloud began raining heavily or if the top of the cloud began to get fluffy (a sign of the start of the demise of the cloud), the aircraft flew on to the next likely area. Flights were generally restricted to within about 100 miles of Key West, provided this was not south of 24° N latitude (i.e., near Cuba). Most of the waterspouts were found within an area 30 miles north of the Keys. The reason for the high frequency of funnels in this locality appears to be that the air is warm and moist everywhere and that the land masses associated with the Keys serve as a sufficient heat source to initiate strong convective action on the lee side of the islands. The wind usually blows at 3 to 10 knots from the southeast during May through September.

When any indication of a water spout was sighted by an observer, and as the aircraft approached the site, cloud and spout were photographed, and the cloud base was determined with the aircraft altimeter. Upon arrival at the event, a cloverleaf pattern (about 2 min on each leg) was flown around the spout at an altitude of around three-fourths that of the cloud base so that the funnel was close abeam of the wing tip on each pass (cruising speed $\approx$ 150 knots). The sensitivity of the electrometers and magnetometer was adjusted to be a maximum for all records obtained. Whenever the instruments indicated a signal of any unusual form, the aircraft would return to that area (on the same and on perpendicular flight directions) to see if the data would repeat, or to see if the cause could be identified. If, after four to ten passes no signals of interest had been received and the funnel was smaller than the aircraft, a pass would be made through the funnel to detect magnetic or electric field signals. Such an adventurous move has been fairly common practice by Navy pilots since before World War II. However, to do so on large severe events would obviously not be advisable (e.g., ref. 33).

On several occasions after the electrical pattern of the cloud had been determined, the aircraft flew to about 100 ft altitude and released a series of smoke markers on the water surface in the path of the waterspout. The interaction of the smoke with the atmospheric vortex indicates the motion of the air near the water surface around the waterspout.

In the flight part of the study, it was necessary to either observe the funnel and cloud at a distance, to move in as close as possible, or to combine the two procedures. It was decided at the outset to make passes close to the funnel (at about one funnel diameter away) because the past experience of Navy pilots had shown it was safe to do so and that the magnetic and electric fields near the funnel are of interest in most electrical theories. Hence, when the close passes were made, the funnel and its parent cloud were not in view part of the time. This procedure, used because the electrical data were of primary concern, caused certain observations to be overlooked; consequently, some data are lacking in table 1 (spaces filled with U for unknown or unobservable). The difficulty of maintaining complete data coverage on each incident was realized because all occur differently and most were of short duration. The large time lags between events and the necessity of rotating pilots and crews added to the problem of proficiency in data gathering.

DISCUSSION OF OBSERVATIONS

It is to be noted that most of the events in table 1 are in what might be called the funnel cloud category, but contact with the water by the vortex was seen in all cases that were observable. Since the purpose of the project was not restricted to events of a certain size or strength, all funnels and vortex patterns sighted were recorded and investigated with the equipment at hand. A differentiation between events will not be made here because an adequate definition of atmospheric vortices is felt to be impossible at this time since too little is known of their characteristics. For example, Webster's dictionary (second definition) defines a waterspout as, "a funnel-shaped or tubular column of rotating, cloud-filled wind extending from an ordinary cumulus or cumulo-nimbus cloud down to a cloud of spray torn up by whirling winds from an ocean or lake." It is questionable then whether some of the events studied should be classed as waterspouts, as water devils, or as water-whirlwinds because of their similarity to dust devils and whirlwinds over land. (The Glossary of Meteorology published by the American Meteorological Society describes a waterspout as a tornado over water.) The ambiguity in naming the various events is further complicated by the fact that the funnel length from the cloud and the spray height generated at the water surface are hard to determine visually and were found to depend on the viewing angle and the proximity of the event. All of the events were unquestionably atmospheric vortices and it is doubtful that different processes were involved but rather that the differing circumstances caused the events to have different characteristics. For convenience, therefore, all the observations will be referred to here as waterspouts or spouts, vortices, events, and whirlwinds interchangeably. The various features of the waterspout funnels and parent clouds are described in the following subsections, before the electrical measurements are discussed because the funnel and cloud characteristics are believed to have a bearing on the electrical properties observed.

Funnel

Shape- When flying at about 1000 ft altitude, it is quite easy to identify likely vortex activity by either a funnel starting down from a cloud base or by a vortex pattern on the water. After seeing only one event, inexperienced crew members could readily distinguish succeeding occurrences from rain, virga, or other cloud pendants by the typically smooth walls and the usually square lower end of the funnel (see fig. 5) during the early phases of the event. All funnels seen from the aircraft had a vortex pattern on the water under them, although the rotational velocity was too weak on several occasions (e.g., 1 Aug. 1968) to identify a direction of rotation. When the vortex is strong, the direction of rotation is easily noted by the rotation of the spray generated (fig. 6) and by the offset of the vortex wake (fig. 7) in the water due to the motion-rotation interaction. Of the vortices that were observable, 30 rotated cyclonically and 9 anticyclonically.

The variation in the strength of the vortices along their length between the water surface and the cloud was, in three cases, such that a funnel was not apparent at the cloud base and, in one other case, a parent cloud was not present at all. These results suggest that the strength of the vortex is not always constant along the column and that this variation is different for different events. That is, in some cases, the vortex is stronger near the cloud than at the surface, and at other times the situation is reversed. Corresponding variations with altitude in the angular momentum of air entering the vortex probably accounts for the variation of vortex strength with altitude. As an example of the possible variations, one of the funnel clouds of 1 August 1968 extended a considerable distance to the water with a barely perceptible water mark (a smooth or polished circular area). At the other limit, a funnel cloud was not apparent on 20 August 1968, even though the vortex was strong enough at the surface to carry spray over one-half of the distance to the cloud. Although this water-devil was located under a cloud, another similar vortex was observed by the project officer, Lt. J. F. Fitzgerald, on 29 August 1968 when the only cloud in the area was a light cirrus deck at 20,000 ft (~6,000 m).

The shape of the axis of the vortex also varied over wide limits, from a nearly straight line between cloud and water, to a serpentine form which had what appeared to be four right angles separated by equal straight-line segments (event on 11 June 1968). Some axes were nearly straight and vertical while others were bent or inclined at 45° or more (fig. 8). One of the funnels observed from USCGC ARIADNE (29 July 1967) made a complete U-turn so that it appeared to reenter the cloud for about 1 min.

No cases were found in which the funnel or spray was unsymmetrical about the axis. Each vortex was different in some respect and many contained cylindrical stratification (figs. 9 and 10) to some degree. Centrifugal separation of water droplets and velocity variations in the core could account for one or two dark cylinders, but the many layers shown in figure 10 appear to indicate additional organizing or separating mechanisms. Such cylindrical stratification from cloud to surface has been observed in the past (e.g., refs. 37 and 38) and appears to be common when lighting is favorable. Whether it exists for a period in all large waterspouts is questionable because rather thorough observations on some waterspouts did not detect such an elaborate stratification (refs. 39 and 36). This organization suggests that air motions are laminar and turbulence appears to be restricted to the vicinity of the vortex-water contact region. Very large waterspouts or events over rough terrain may have less, if any, laminar flow. Cylindrical stratification found by Turner (ref. 40) for a laboratory vortex may be due to recirculation of the fluid and is therefore probably not related to that shown in figure 10.

Velocity- The velocity listed in table 1 is a lower bound calculated from the funnel length according to appendix B. No relationship was found between the strength or velocity of rotation of the vortex and its size, nor was the strength and velocity related to the size or shape of the cloud. Rather, the phases of the waterspouts suggest a much larger initial diameter at the cloud base than at the surface but the funnel becomes more nearly cylindrical as the vortex ages (fig. 11). Also, the square lower end (fig. 5) often becomes more nearly pointed in later stages if it does not extend to the surface, suggesting that the air with low angular momentum has been expelled upward into the cloud. A funnel that appears weak at a distance is often found (when the crew has a close look at the vortex) to have a high-speed core that produces a low-density funnel all the way to the surface and raises considerable spray (e.g., fig. 6). A pointed lower end and the change in appearance with distance of observation from the vortex are also illustrated in figure 12 for a tornado. Note the similarity in cloud structure and relationship to funnel shown in figure 12(a) with the waterspout pictured in figure 6(a).

In keeping with vortices constructed with a single cylinder, many events were noted to have a calm center separated by a ring of agitated water from the rest of the wave pattern on the sea (fig. 7). Consideration of the circular velocity v, dynamic pressure $q = 1/2\rho v^2$, and work capability vq for a Rankine vortex shows that the calm eye surrounded by a turbulent ring is reasonable. That is, if

$$v = r\Omega \qquad \text{for} \quad r \leq r_o$$

$$v = (\Omega r_o^2/r) \qquad \text{for} \quad r \geq r_o$$

then, the curves of v, v^2, and v^3 appear as indicated in figure 13. As the velocity of rotation reaches and exceeds a certain critical value (estimated at 30-50 m/s), the spray generated on the water increases rapidly (cf. figs. 6 and 7).

As mentioned previously, smoke flares were dropped on the water near several waterspouts to see if streamlines could be traced. Although the smoke diffused rapidly, it did indicate the flow pattern on several events, the best of which is shown in figure 14. As expected, the cyclonic flow field of the vortex is much larger than the funnel. Also the smoke trail indicates clearly an inflow with rotation (sink-vortex combination). A quantitative estimate from the photograph for the strength of the vortex-sink relationship (i.e., radial inflow velocity/circumferential velocity $\simeq 1/16$) is unreliable because the vortex was moving upwind at an unknown velocity.

The waterspouts usually appeared to be stationary during the initial or early part of their lives unless rainshowers were nearby. Then, or later on and until the spouts quit, they would often move over the water at speeds of about 60 knots. No single preferred direction of motion was apparent. Sometimes the vortex on the water would make a circle or wander aimlessly. This erratic behavior coupled with the motion of the aircraft made it difficult to place the smoke flares on the water where desired. The bottom end of the funnel usually moves away from any rainshowers nearby because of air entrained by the rain. Hence, funnels near rainfall lean so that their tops are nearer to the rain than are the bottom ends.

Demise of waterspouts- Waterspout funnels were observed to have their demise in three different ways.

(1) Funnel withdraws into cloud as if air with angular momentum was depleted or updraft was terminated.

(2) Funnel merges with rainshower and disappears from view because of density of rain or because rainfall overcomes vortex or updraft motion or both (see fig. 15).

(3) A lightning bolt beside a funnel caused the funnel to break into pieces as if made of glass. This happened on one occasion (9 Aug. 1967). The pieces then evaporated in about 1 min (see fig. 16).

On no occasion did flying the aircraft in or near a funnel disrupt the funnel long enough to be observed. This indicates that reports of breaking up waterspouts with cannon fire were coincidences and in sea stories of so-called "venting of the funnel" did not cause the demise of the spout. The large extent of the flow field of the vortex shown by the smoke flare in figure 14 in comparison with the size of any turbulence or vorticity that could be generated by the aircraft suggests that a vehicle of considerable size and disturbance energy would be required to disrupt even a small water spout unless the disturbance found a sensitive spot on or near the funnel. The reason why the lightning bolt apparently caused the rapid disintegration of a funnel on 9 August 1967 is unknown but the occurrence suggests that such a sensitivity may exist in these atmospheric vortices.

Parent Cloud

Most waterspout funnels occurred under isolated cumulus clouds that had tops around 6,000 to 10,000 ft (1,800 to 3,000 m) and bases at 800 to 2,500 ft (240 to 750 m) (e.g., fig. 6). Another group was found under low cells (tops 6,000 to 10,000 ft) at the end or in the middle of a row of clouds wherein some had tops in excess of 25,000 ft (e.g., figs. 17 and 18) and some of which had anvils. No funnels were found under the large clouds or cells themselves when tops could be seen to exceed about 15,000 ft. When the funnels occurred in cells near tall clouds (e.g., fig. 18), lightning and rainfall were often present in and under the large cells but did not appear in the parent cell until the funnel had disappeared and the top had grown further. In all cases the funnel was very small in comparison with the size of the cloud or cell. A rainshower would often start while the funnel was still in existence and the two would sometimes merge. At no time did the rain stop and a funnel form afterward. The relationship between the funnel and clouds for the waterspout appears to resemble that shown for tornadoes in figure 7 of Fulks (ref. 4) or perhaps in Bates (ref. 41) rather than that in

Browning (refs. 27 and 28). Comparison of the events shown in figures 6(a) and 12(a) suggests that tornado and waterspout events can resemble one another, at least on occasion.

In the remainder of this section some general characteristics and several unusual occurrences will be described. One case, felt to be unusual, occurred on 8 August 1968 after the daily flight had been completed at 1810 EDT. Four waterspouts were seen in succession as they appeared from clouds whose depths were less than the distance of their bottoms from the surface (see fig. 19). The tops of the clouds appeared soft or fluffy, indicating subsidence or at least not rapid growth. After the four spouts (extending one-fourth to one-third of the way to the surface) disappeared (about 20 min total), the cell tops over the spout locations swelled upward growing rapidly for about 5 min. From the observation point, it appeared that rain did not fall and the cloud growth did not progress above about 6,000 ft. The foregoing sequence indicates that the buoyancy of the local air in the vortex drives it and this air reaches the cloud top after it has passed through the event. If such is the case, hooks or eyes seen in radar echoes, when waterspouts and tornadoes occur, must be associated with air that has risen beyond the vortex and therefore follows rather than accompanies the event - especially if the funnel is of short duration. Spiral rain patterns under clouds were also found to occur on occasion (e.g., fig. 20) even though a waterspout was not observed prior to or following the rain pattern.

Although the clouds wherein waterspouts were observed were usually isolated cumulus, a number of events were seen from rows of clouds or from a continuous line of convective cells. In such cases (especially 8 Aug. 1968, see figs. 17 and 18), cells would form at one end of the chain and grow to the size of the rest of the clouds with new cells forming in sequence so that a graduated system was always present. Waterspouts would appear in the various new cells as they reached a certain size (top ~4 to 8,000 ft) and then the spout would disappear when the tops approached or exceeded about 12,000 ft. Motion of the complex of clouds and the formation of the new cells with the vortices forming in sequence would give a track for the successive vortices which would be broken segments parallel to each other and alined or offset depending on whether the wind was parallel to the cloud-line or offset in much the way that has been observed for tornadoes.

While observers waited for waterspouts to occur, they surveyed the air temperature profile using the aircraft thermometer. Typical readings are presented in the table on the next page.

Flights were also made over and through the tops of low cumulus cells developing in the area to find out if the clouds were electrified. The air in the tops was frequently composed of a large number of small droplets that bathed the aircraft as if it were in a moderate rainshower. Rain fell from clouds that had tops as low as 5,000 to 6,000 ft but electric fields were not found until the tops exceeded 10,000 ft (~ +13C) and lightning did not occur until the tops were over 13,000 to 15,000 ft ($T \approx +3C$).

Aircraft altimeter, ft	Temperature, °C		
	7 August 1968	14 August 1968	24 September 1968
0	29	30	30
500	28	29	29
1,000	26.5	28	27
1,500	26	27	25.5
2,000	25	26	24
2,500	24	25	24.5
3,000	23.5	24	23
3,500	22	23	22
4,000	21	22	21
4,500	20.5	21	20
5,000	20	20	20
5,500	19.5	20	19.5
6,000	19	19	19
6,500	17	18	16.5
7,000	16	17	15
7,500	16	16	15
8,000	15.5	15	15
8,500	15	14	14
9,000	14	14	12.5
9,500	13	13	11
10,000	12	12	11

As mentioned by other observers of waterspouts, cloud conditions favorable for waterspouts tend to form downwind from land (the Keys) and the more active areas were associated with larger land masses (i.e., Key West vicinity and near Marathon). Waterspouts did not occur on overcast days, nor on days when the temperature was nearly constant for 1,000 to 2,000 ft in the 5,000 to 8,000 ft level. The most productive days were those wherein sky was clear except for strong, scattered rainshowers. Spouts occurred while the clouds were forming. Once a cloud started raining profusely no events were found.

Some similarities appear to exist between waterspout and tornado clouds, at least on occasion. The general form, depth, etc., of the cell configurations shown in figures 6(a) and 12(a) closely resemble one another even though figure 6(a) is a cloud over water at sea level and the tornado in figure 12 is over land at 8,000 ft elevation. (The tornado occurred while TenBroek and Seashore (ref. 42) were studying storm fronts over Colorado.) Although the photographs of the Wichita Falls tornado are very good (ref. 43), not enough is shown of the parent cloud to compare it with waterspouts. It would be interesting to compare clouds over a number of tornado events to see if similarities persist or what difference can be found in the cloud structure. The photographs should include the tornado and parent clouds at a distance far enough to include most of the cloud and close enough to see the funnel clearly. Since the waterspout clouds observed were all too low to interact with a jet stream, a relationship of the latter with the waterspout occurrence, such as has been considered for tornadoes (ref. 31), is unlikely. Radar studies of funnel-cloud combinations such as the one made by Hiser (ref. 44) are also necessary in comparing waterspouts and tornadoes.

Funnels appeared from cloud bases that were both smooth and had considerable virga (e.g., figs. 5, 6, and 18). A cloud base with a large section protruding downward usually produced a heavy rainshower (fig. 18(b)). While on board the Coast Guard Cutters, it was noted that all clouds that spawned spouts gave good radar returns, indicating the presence of water-droplets, and only a very few (e.g., 19 Aug. 1968) did not produce a rain-shower while the funnel existed or shortly after. The air under parent clouds was quite smooth and a slight roughness (like a bumpy road) was experienced as the aircraft flew through the smaller events. On several occasions (e.g., 18 July 1968) a definite yaw and roll of about 5° each was experienced as the aircraft went through the vortex. Waterspouts did not appear when the air under a cloud was rough and turbulent, nor on windy days ($V > 10$ knots) with waves over 3 ft. Downdrafts noted several times near a funnel may have been due to rain-induced subsidence of the air or due to air drawn downward by a low pressure region between the cloud base and the surface brought about by spin-up of the vortex.

ELECTRIC AND MAGNETIC FIELDS

In the past, data on the electrical nature of atmospheric vortices have been obtained on an accidental or coincidental basis with the exception of some measurements on dust devils (Bradley, ref. 45; Crozier, ref. 46; Freier, ref. 47; Lamberth, ref. 48; Sinclair, ref. 49). Reports gathered by Vonnegut and his associates (Thorarinsson, ref. 50; Vonnegut, refs. 5-8) are evidence of electrical activity but since the fields were not measured, the relationship between the vortex and electricity is uncertain. Magnetic field and ground current measurements made by Boucher and reported by Brook[3] (ref. 13) provide some data on the electric current characteristics, but uncertainties in the position relative to the funnel and cloud make it difficult to interpret and apply the measurements. These measurements and observations made accidentally provided a strong stimulus and a guide for making a systematic attempt to obtain electric and magnetic fields near atmospheric vortices.

An order-of-magnitude analysis is presented in appendix A for several electrical theories for tornadoes and the results are presented in figure 21. The theoretical work yields only the exponent of the variation of the magnetic field with diameter. To provide a graphical representation, the point of departure for all the curves was chosen where $D = 10$ m and $B = 0.01\gamma$ ($1\gamma = 10^{-5}$ gauss) because a number of events about 10 m in diameter were found not to have a detectable magnetic anomaly[4] (i.e., $B \lesssim 0.01\gamma$). The data are

[3]See footnote 1, page 2.

[4]The signals provided by the MAD equipment are referred to as magnetic anomalies because the filters and sensor are such that only changes in the magnetic field component along the earth's field direction are registered if they are between 0.075 and 0.75 cps.

shown as rather large ellipses to indicate the probable error due to known sources of uncertainties associated with each. If the signals result from, or are associated with, other phenomena in the area (e.g., changes in aircraft altitude or activity in nearby clouds), then the interpretation must be altered accordingly. No data are shown for the 1968 flight program wherein the aircraft was instrumented with both electrometers and a magnetometer. One reason is that no large, severe events were encountered during that time. In the events found, the electric and magnetic fields usually could be attributed to causes other than the activity associated with the atmospheric vortices. Some of these are:

(1) Charging of the aircraft due to its passing through precipitation (see fig. 22(a));

(2) Lightning and charges in other clouds (see figs. 4 and 22(b));

(3) Altitude changes (fig. 22(c)) and rough air (fig. 4) which affect the magnetometer but not the electrometer readings;

(4) Turning electrically driven cameras on or off (fig. 22(a)); and

(5) Roll, yaw, or pitch of aircraft in the presence of an electric field (results in cross coupling of components) (see fig. 22(c)).

These false signals could usually be identified by making repeated passes or by checking the gear under other conditions. Since 4 to 10 passes were made on each funnel, it was possible to check rather thoroughly any promising signals.

The data which could not be discarded or attributed to other causes are those of Brook (ref. 13) and three events in 1967. Samples of the magnetic tapes for the flight data (fig. 22) show that an experienced operator is required to discern an authentic magnetic signal if it is weak, and even then the validity of the signal is questionable. The data are included in figure 21 because there is no good reason to say they are not valid but the curves are not well enough defined to use in a calculation.

Whenever large clouds were in the area around or near a waterspout cloud, lightning was often indicated on the data tape (figs. 4 and 22(b)) by both a near discontinuity in the electric field components and by a pulse in the magnetic anomaly. The lightning bolts seen were usually at a distance of 2 to 10 miles from the funnel and in only one case (9 Aug. 1967; number 16) did a lightning bolt occur near a funnel or its parent cell. This funnel was the third in a series of four from the same cloud bank. As the Cutter ACTIVE passed under the cloud, the funnel and the spray at the surface could be seen clearly through binoculars (distance estimated at 3 to 5 mi). While Harold Clements of Ames, several members of the crew, and the author were watching the funnel through binoculars, a single stroke appeared beside the funnel-cloud juncture as sketched in figure 16. Within about a second the funnel appeared to have seams or to have broken into pieces (like a glass lampshade). The pieces drifted apart slightly as they evaporated. (The visible funnel extended over halfway to the water.) During the time of appearance of the funnels, the radioman noted that his radios were essentially jammed with static. An opportunity to view the superstructure of the cloud did not come because other clouds obstructed the view. Further data are not available to determine whether, or the manner in which, the lightning bolt caused the demise of the spout.

Only six of the 1968 events had an electric field over 100 V/m (three at about 2,000 V/m, two at about 20,000 V/m, and one at about 10^5 V/m) associated with clouds in the vicinity of the funnel and none were attributed to charges or currents within about one-half mile of the funnel. Lightning strokes were indicated by the instruments while near spouts on four occasions but in only one instance could the strokes have been in the cloud or cell over the vortex (a funnel cloud was not apparent in this case even though the water spray rose halfway to the cloud).

The low altitude (i.e., between 8,000 and 12,000 ft (2440 to 3650 m)) observed for the top of the parent cloud over the vortex was found to be below the altitude for which appreciable cloud electrification occurs. Because these cloud tops were so low, measurements were made on growing clouds and it was found that electrification does not become appreciable until the cloud tops reach and exceed about 13,000 ft. Many of the waterspout clouds grew to appreciable altitudes after the funnel had quit and then produced lightning, but this followed rather than accompanied the occurrence of the vortex. On no occasion were regular pulsations observed like those seen with the Blackwell tornado, although occasional strokes spaced at 6 to 10 s intervals were detected under some clouds without waterspouts. Also at no time did an electric field measured near a waterspout resemble the field measured on dust devils (refs. 45-49). It is not known whether the different electrical character arises because charges leak off around waterspouts because of the high moisture content of the air, or because dry dust or debris is required for triboelectric charging of the vortex.

The measurements made in the present investigation indicate that no electrical characteristic appears to be associated with waterspouts. Without a doubt, the magnitudes observed are not a function of the diameter or intensity of the event. This also is in agreement with the fact that the velocity of rotation and diameter of the funnel are not related uniquely. These results suggest that velocity, diameter, electrical effects, etc., are governed by a flow characteristic not considered herein. Although electricity can be rejected as important in the events studied during 1968, its role in the spouts on 7 June 1967, 9 August 1967, or in the events reported by Brook and Vonnegut cannot be evaluated. The data obtained with the project aircraft do not explain these occurrences and it is felt by the author that none of the theories proposed so far (especially the author's) describe adequately the role of electricity in events where strong activity was observed. The fact that electricity can accompany atmospheric vortices and that these vortices can exist without a significant electric or magnetic field suggests that of all the competing theories, the electrification and discharge process (triboelectricity generated by vortex air/debris interaction (Platou, ref. 51; Lavan, ref. 52)) proposed by Loeb (ref. 53) and others is probably the best explanation put forth so far because there are no grounds for rejecting that theory.

The possibility that important electric or magnetic fields existed and were not detected is believed unlikely because the gear responded to lightning strokes at the upper end of the spectrum and the electrometers, to steady voltages (i.e., frequency = 0) at the lower end. The magnetometer did not, however, detect fields that varied much more slowly than 0.075 cps, although a response was indicated for all higher frequencies. Late arrival at an event or short duration phenomena also did not cause us to miss data because of the large number of events seen and almost continuous measurement from very early inception of the vortex (i.e., from when the funnel or the vortex on the water was first evident).

In arranging for the present project, the author was introduced to James Beville of Miami by James Stahmann of R. V. THUNDERBOLT in Miami. Mr. Beville told of an incident he observed that was remindful of the theory proposed by Rathbun (ref. 54) for the initiation of a waterspout. He observed a stroke of lightning from cloud to water in the Gulf of Mexico near Big Pine Key. As if the lightning channel left a residue of smoke, a waterspout started up and persisted for several minutes before withdrawing into its parent cloud. He has seen a number of funnels while fishing and knows of no other similar occurrences.

CONCLUDING REMARKS

The results found in the present study indicate that small waterspouts can exist without support from electric or magnetic fields even though the rotational velocities exceeded 100 m/s on occasion. This does not rule out, however, the possibility of a contributory role in the structure of tornadoes or more intense waterspouts on occasion. In particular, the results do not explain observations such as those reported by Vonnegut and Brook wherein electrical displays or strong electric currents accompanied or were in close proximity of tornadoes. But, electrical characteristics definitely cannot be used to locate, forecast, or identify waterspouts. Certain data (i.e., low cloud tops and lightning demise) indicate that electrification of a special sort may prevent or eliminate a waterspout; that is, small forces in certain locations may have profound influence on the vortex structure.

The applicability of the data on the events described here to larger and more intense waterspouts and to tornadoes is questionable. The location of the funnel relative to the tall clouds, the jet stream, etc., indicates that substantial differences may exist on occasion.

A relationship between the funnel diameter, the maximum velocity of rotation, cloud size, etc., based on visual parameters does not appear to exist. Also, a defining mechanism that identifies the circumstances necessary for the formation of a vortex under one cloud rather than any of the others was not found. This suggests that theoretical studies and measurements be made to find a necessary or defining relationship.

Two final comments are felt to be pertinent regarding the conduct of the study. First, as pointed out by Harold Gerrish, the waters around southern Florida (and especially the Keys) appear to be a prolific producer of waterspouts. Second, the mobility of a reliable aircraft (cruising speed $\approx$ 150 knots) and its ability to make passes near the funnel are essential.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Dec. 29, 1969

APPENDIX A

VARIATION OF ELECTRIC AND MAGNETIC FIELDS WITH SIZE OF VORTEX FOR VARIOUS MODELS

Before a choice can be made of the instruments to be used in measuring the electric and magnetic fields likely to be associated with vortices, an estimate for the magnitudes and possible variation of these fields with time and distance must be made to determine the characteristics desired for the equipment. Since a number of models have been proposed and the small amount of experimental data available is not definitive enough to indicate a single theory or process as the one to consider, several models which are felt to be typical of the theories proposed were used to estimate the fields to be expected. It is assumed that the process being studied is the primary drive although the possibility that it is an organizing, augmenting, or supplemental force should not be overlooked in examining experimental data. The size of the funnel will arbitrarily be defined as the visible diameter of the funnel at the midpoint between cloud and surface.

ELECTROSTATIC MOTOR DRIVE

Viscous Restraint

Observations and discussions by Vonnegut and the laboratory and theoretical work of Silberg (refs. 14-16) were extended by Rossow (ref. 18) to study the possibility that tornadoes or waterspouts derive their angular momentum from an electrostatic motor type action in the parent cloud. The proposed model assumes that an interchange of charged water droplets and air between two charged regions of a cloud bring about a circulation of the air which might be instrumental in forming the atmospheric vortex. Charged air convected from one place to another can produce a so-called electrostatic vortex if an updraft concentrates the rotating motion to produce a vortex. If the flow is steady, the only restraint on the velocity is the viscous interaction of the vortex with its surroundings. Hence, it is found that the electric current for such a vortex is proportional to

$$I \sim \rho_e{}^2 E D^4/\eta \tag{A1}$$

where ρ_e is the charge density (C/m^3), E the electric field intensity (V/m), D the diameter of the vortex, and η a viscosity representative of the flow field. It was also assumed in equation (A1) that the cross-sectional area of the channel through which the charged air is being convected is proportional to D^2. In this model, the forces are not of interest unless the electric field is as large as possible which would be near breakdown. When the test aircraft passes a funnel, it should then measure an electric field of 10^5 or 10^6 V/m which peaks near the event and then falls fairly rapidly with distance from the vortex. If it is assumed that E and ρ_e are a maximum and nearly the same for all events, the electric current will vary as the fourth power of the diameter. The magnetic anomaly to be expected would be steady with time but vary spatially. The change with distance can be estimated by calculating the magnetic field of the electric current associated with this or any model by use of the integral

$$\vec{A} = \frac{\mu}{4\pi} \iiint_V \frac{\vec{J}(x_1, y_1, z_1) dx_1 \; dy_1 \; dz_1}{[(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2]^{1/2}}$$

where $\vec{A}$ is the magnetic vector potential, $\vec{J}$ is the local electric current density at the integration point (subscript 1), μ is the magnetic permeability, and V is the volume over which the integration is made (i.e., where $\vec{J}$ is nonzero). It would be difficult to account for the separate and large number of small discharges occurring on the periphery of the electrostatic vortex in addition to the curved current channels. If, however, the point of observation is far away, the electric current system can be idealized to a straight current filament of length $2l$. In this, it is also assumed that the gathering and dispersing currents near the ends are part of the straight-line approximation (e.g., this model represents the magnetic field of the current through a wire between two large condensers). The magnetic vector potential for such a simplified system is then given by

$$\vec{A} = \frac{\mu}{4\pi} \int_{-l}^{+l} \frac{I\hat{i} \; dx_1}{[(x - x_1)^2 + y^2 + z^2]^{1/2}}$$

where, for convenience, the current is assumed to be along the x axis from $-l$ to $+l$ and of constant magnitude I. On integration of this expression,

$$\vec{A} = \frac{\mu I \hat{i}}{4\pi} \left(\sinh^{-1} \frac{l - x}{\sqrt{y^2 + z^2}} + \sinh^{-1} \frac{l + x}{\sqrt{y^2 + z^2}} \right) \tag{A2}$$

The magnetic field components are found from $\vec{B} = \nabla \times \vec{A}$ to yield

$$B_x = 0 \tag{A3}$$

$$B_y = \frac{\partial A_x}{\partial z} = - \frac{\mu I}{4\pi} \left[\frac{l - x}{\sqrt{(l - x)^2 + y^2 + z^2}} + \frac{l + x}{\sqrt{(l + x)^2 + y^2 + z^2}} \right] \frac{z}{(y^2 + z^2)} \tag{A4}$$

$$B_z = \frac{-\partial A_x}{\partial y} = \frac{\mu I}{4\pi} \left[\frac{l - x}{\sqrt{(l - x)^2 + y^2 + z^2}} + \frac{l + x}{\sqrt{(l + x)^2 + y^2 + z^2}} \right] \frac{y}{(y^2 + z^2)} \tag{A5}$$

When $l \to \infty$ these expressions reduce to those for the field around a wire that is infinitely long. At distances of 1 and 10 km from the electrostatic vortex, the magnetic field is roughly 10^{-4} and 10^{-6} gauss, respectively (or 10 and 0.1 γ) for $I = 100$ A, and l of 1 km. Since the aircraft usually passes within about 100 m of the waterspout funnel, a rule of thumb used is that a 1 γ signal indicates a 1 A current in the vicinity of the funnel.

In order to obtain insight into the variation to be expected in the magnetic field as the aircraft flies around a possible current configuration, a number of situations were calculated. Graphs of these results provided a catalog with which data could be compared as a first step in the data reduction and as a basis for choosing the test equipment. The two examples presented in figure 23 illustrate that differences between current configurations are large enough to distinguish them by their magnetic profiles. It is to be noted that even though these values for the magnetic field are small when the current is of the order of 1 A, such fields are detectable with equipment used to measure interplanetary magnetic fields and used in airborne submarine detection.

Inertial Restraint

When tornadoes and waterspouts were presumed to be an inward and upward flow of air and no mention had been made of a rotary motion, a number of persons suggested the possibility that electricity was largely responsible for the low pressures and large in-flow rates of tornadoes (e.g., refs. 1 and 2). The qualitative models proposed then have been enlarged upon and studied with approximate theories by Vonnegut (ref. 5), Silberg (ref. 14), and others. In order to estimate a current/diameter relationship that will typify this process, it will be assumed that the electrostatic body force accelerates a parcel of charged fluid from rest and without friction, or other losses, over a distance equal or proportional to the characteristic diameter of the funnel. Any velocity induced in this manner will also be assumed to be the same whether it is along the funnel (say up its center) or whether it is tangential (circumferential contribution to rotary motion); that is, $v_{vertical} \approx v_{horizontal} \approx v$. The force on a parcel of charged air and its resultant motion are given by

$$\vec{F} = \rho_e \vec{E}$$

$$\vec{a} = (d\vec{v}/dt) = (\rho_e/\rho)\vec{E}$$

If all parameters are taken as nearly constant,

$$v = (\rho_e/\rho)Et = ds/dt$$

then,

$$s \approx D \approx \rho_e E(t^2/2)$$

whereby

$$t \approx (2D/\rho_e E)^{1/2}$$

and

$$v \approx (2\rho_e ED/\rho)^{1/2} \tag{A6}$$

The current for such a process is then found as proportional to

$$I \sim \text{(Area)(charge density)(velocity)}$$

$$\sim D^2 \rho_e v = D^{5/2} \rho_e (2E/\rho)^{1/2} \tag{A7}$$

Hence, the variation of magnetic field with size of the funnel is proportional to the 5/2 power of diameter.

Time-Varying Electrostatic Force

Observations of pulsating electrical discharges around and inside the funnel of the Blackwell, Oklahoma, tornado on 25 May 1955 (ref. 55) and Jones' observations of a "tornado pulse generator" (ref. 9) led Silberg (refs. 14-16) to study theoretically and experimentally the possibility that a ring current could drive a vortex and under what conditions. Estimates of the electrical energy stored in a thundercloud suggested that a tornado could be produced by electrical energy stored in the parent cloud that manifests itself as a ring current whose inductive impulse fields could produce vortical motion. Qualitative laboratory experiments confirmed that rotary motion could be achieved in solid and gaseous rotors with high voltage electric fields that are initially electrostatic. Theoretical estimates (ref. 14) of the electrophoretic and dielectrophoretic force fields yielded the velocity and therefore the current and magnetic field to be expected. In the electrophoretic (i.e., charge convection) case, it was assumed that the electric field could be represented by

$$E = E_0 e^{-\beta t} \sin \omega t \tag{A8}$$

and the velocity by

$$v = (e/M)E_0 10^7 \int_0^\infty e^{-\beta t} \sin \omega t \, dt$$

$$= 3.26\times10^5 \; E_0 \text{ cm/sec} = \text{velocity contribution/electrical pulse} \tag{A9}$$

where $\omega >> \beta$, M = 30 proton masses and E_0 is in V/cm. To estimate the field configuration, the electric field will again be a maximum of the order of 10^5 to 10^6 V/m but pulsating, and the electric current is approximated by

$$I \sim \rho_e D^2 vN \tag{A10}$$

Since a relationship between the number of surges of electricity N and diameter is not known, equation (A10) will be left in this form. Observations of the Blackwell tornado and Jones' observations of other tornadoes (ref. 9) suggest a pulsating frequency of the order of 20 to over 150,000 cps. A means for associating these numbers with either ω or N remains to be found. The analysis by Silberg (ref. 14) showed that the dielectric force field would augment the electrophoretic action but would be enough smaller in magnitude to be negligible.

AUGMENTATION OF BUOYANCY DUE TO ELECTRICAL HEATING

After studying the structure of vortices in buoyant air, Vonnegut (ref. 5) and others concluded that, for the models assumed for the vortex, some sort of additional uplift is required to obtain velocities in the vortex much over about 100 m/s. Various mechanisms were then considered theoretically with the result that electrical heating (Ohmic or Joule) of air around and in the vortex to increase its buoyancy seemed the most plausible. Experiments and further theoretical work were carried out by Vonnegut (ref. 5) and Wilkins (ref. 17). Colgate (ref. 19), in the light of a measurement reported by Brook (ref. 13), enlarged upon the calculation and proposed means to reduce any electrical influence that might occur.

Prior work is adapted in an approximate fashion to the present need for a relationship between size of the event and a possible magnetic anomaly due to Ohmic heating in the atmospheric vortex. That is, the velocity achieved is related to the buoyancy by

$$v^2 \approx h\ \Delta T \approx (RJ^2/C_p)h \tag{A11}$$

where ΔT is the temperature difference along the entire vortex column, h, and the density reduction achieved between the surroundings and the core of the vortex are taken at constant pressure so that $\rho_1/\rho_2 = T_2/T_1$. The electric current density, J, and resistivity of the air in the core, R, determine the heat added to each kilogram of air. Since a relationship between the size of the vortex and the velocity achieved is not available, the velocity will be assumed to vary linearly with diameter D. The total current, I, along the vortex core is then

$$I \approx \text{area} \times \text{current density} \approx D^2 J \tag{A12}$$

or by equation (A11), $I \approx D^3$. Other assumptions regarding the velocity/diameter dependence or on the process being considered will result in other forms for equation (A12).

MISCELLANEOUS THEORIES

Various other electrical mechanisms have been proposed for the structure of the vortex or for certain of its phases (e.g., refs. 55 and 56). Some descriptions of theories that date back 100 years or more are so brief that it is not possible to find an approximate representation of the process proposed. Therefore a relationship is not calculated for them but their possible application must be recognized when the data are studied. Also, nonelectrical theories that consider electrical displays a result of the vortex motion rather than a cause belong in the category of this appendix (e.g., ref. 53). For example, such an occurrence is characterized by electric field readings that are quite high but confined to the immediate vicinity of the funnel. Any magnetic anomaly associated with the event will be near or below the threshold of the instruments.

APPENDIX B

ESTIMATE OF VELOCITY IN VORTEX

The pendant that appears to hang from the parent cloud of the waterspout consists of water droplets that result from condensation of vapor contained in the moist air entering the vortex. The outer boundary of the droplet volume, which includes the visible funnel and the cloud base, is a nearly constant temperature surface if the air crossing that boundary is homogeneous. That is, at this surface, air is cooled by a decrease in pressure caused by an increase in altitude and velocity so that it cools to the temperature at which condensation begins. If the number density of water droplets is large enough, this condensation surface can be seen. The objective here is to relate the vertical length of the funnel beneath the cloud (see fig. 24) to the velocity at the outer edge of the condensation surface. Since it is difficult to see the onset of condensation that defines the extremity of the funnel (especially its lowest point) and the base of the cloud, the size of the funnel will be underestimated. This fact and the occurrence of some lag between the time that the air has cooled to the dew point temperature and when an appreciable number of droplets appear, cause the velocity estimate here to be conservative in the sense that the value calculated represents a lower bound on the speed. That is, at some place in the funnel the velocity is equal to or greater than that calculated by this method. It is also assumed that the total energy of the air entering the vortex is the same as that entering the cloud base. (The dry adiabatic lapse rate of 0.977° K/100 m should then be used for the flow field beneath the cloud rather than the normal lapse rate of 0.65° K/100 m (NACA Standard Atmosphere).)

To derive an equation that relates the funnel length to the velocity, the flow field below the cloud and around the funnel is assumed to be isoenergetic, adiabatic, and isentropic so that the energy of the air can be written as

$$(u_r^2 + u_\theta^2 + u_z^2)/2 + gz + C_pT = C_pT_o$$

or

$$v^2/2 + gz + C_pT = C_pT_{cb} + gz_{cb} \tag{B1}$$

where T_o is the stagnation temperature of the air at the surface (z = 0, and T_{cb} and z_{cb} are the temperature and altitude of the air at cloud base far from the funnel. Equation (B1) does not apply in the viscous boundary layer on the surface of the earth, in the core of the funnel, nor in the regions where condensation has occurred because those areas are not related adiabatically and isentropically to the rest of the flow field. Neglecting the core in the analysis is felt to be reasonable because most of the funnels observed and shown in the foregoing text appeared hollow, suggesting that appreciable condensation occurs in some region outside a central volume of the vortex, usually referred to as the core. Hence, the square lower end and the hollow appearance of the funnels is used as justification for the use of equation (B1).

If the exterior of the funnel is assumed to have a constant temperature (i.e., $T = T_{cb}$), the velocity at the outer part of the funnel is related to the distance below the cloud by

$$v = \sqrt{2g(z_{cb} - z)} \tag{B2}$$

or, if Δz denotes the maximum length of the funnel (see fig. 24),

$$v \geq (2g\ \Delta z)^{1/2} \tag{B3}$$

The sign $\geq$ is used to signify that this velocity is a conservative estimate for the reasons mentioned previously and because the velocity inside the funnel probably exceeds this value. Values of v are presented below for a range of funnel lengths.

Δz, ft/m	v, m/s
0/0	0
100/30	24.5
500/152	54.7
1000/304	77.3
1500/456	94.7
2000/609	108.7
2500/751	122.3
3000/913	134.0

A similar result, which differs from equation (B3) by a factor of $\sqrt{2}$, has been derived by Fendell and Dergarabedian (ref. 57). With their assumptions regarding the structure of the core and vortex, they found that, for a given altitude, the pressure at the center of the funnel is half that at the edge of the core. Their estimate for the velocity then differs from equation (B3) by a factor of $\sqrt{2}$. Therefore, it is believed that in those cases where the funnel core is not hollow but is filled with droplets so that its outer surface is smoothly contoured to a blunt point, the Fendell-Dergarabedian result is a better approximation than equation (B3).

Equation (B3) was also derived by Ferrel (pp. 354 ff of ref. 58) by balancing the component of centrifugal force along an isobaric surface of the rotating air against the corresponding component of the gravitational force. Although Ferrel later (pp. 401 ff) identified the outside of the visible funnel as an isobaric surface, he did not use his form of equation (B3) to estimate the velocity in the vortex but appeared to prefer the relationship,

$$rv = r'v' = \text{constant}$$

where the reference quantities $r' = 1000$ m and $v' = 3$ m/s were chosen as typical. It seemed appropriate, therefore, to present the foregoing material because the derivation in this appendix differs from Ferrel's and because he did not indicate the use of equation (B3) as a lower limit on the estimate for the velocity in the funnel.

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TABLE 1.- TABULATION OF ENCOUNTERS WITH ATMOSPHERIC VORTICES

						Cloud			Funnel				Electrical			Comments
Event	Commanding officer	Location from Key West miles/direction	Date	Time: EDT	Duration, min	Altitude of cloud base, m	Top of cell or cloud, m	Maximum width of cloud, miles	Diameter, m	Length down from cloud, m	Inferred minimum wind velocity in vortex, m/s	Direction of rotation	Maximum intensity within 2 miles of spout	Lightning during funnel life	Maximum identifiable magnetic anomaly, γ	
1	Lcdr. J. Gruenenwald P2V; VS-39	170/050°	6-7-67	1000-	>30	300	3000	U[1]	30	300	77	C[2]	---	Yes, and radio interference	Appeared as ~1γ noise on MAD gear	Spout and cloud appeared to produce about 1γ of noise on MAD gear.
2	Cdr. J. Fueschel CGC DILIGENCE	102/102°	6-8-67	1615-1625	10	600	3000	U	10	120	49	U	---	None	---	No rain fell from cloud but cloud showed on radar.
3	Lcdr. J. Gruenenwald P2V; VS-39	108/069°	6-9-67	1000-	U	270	U	U	10	160	56	C	---		<0.2γ	Photo of vortex and wake on water shown in figure 7(a).
4	---------do---------	262/062°	6-9-67	1330-	U	300	U	U	6	75	38	C	---		<0.2γ	
5-8	Lcdr. C. Holland CGC ARIADNE	183/117°	7-29-67	0930-1030	~5 ea.	600	1800	>5	10	150	54	U	---		---	For a short time, one funnel appeared to make a complete U-turn to reenter cloud.
9-10	Cdr. W. G. Dick CGC ACTIVE	8/180°	8-7-67	1615-1643	16 and 11	600	2000	>5	20	100	44	U	---	None	---	Clouds in area were decaying but cloud over these 2 spouts appeared to be growing.
11	Lt. Radik S2E; VS-28	273/073°	8-7-67	1625-	U	270	U	U	U	U	U	U	---		<0.3γ	A second and small spout formed nearby and lasted ~5 min.
12-13	Cdr. W. G. Dick CGC ACTIVE	156/127°	8-9-67	1000-	.8 ea.	600	U	>5	10	300	77	U	---		---	
14-17	---------do---------	94/126°	8-9-67	1615-1650	10 ea.	300	U	>10	15	150	54	U	---	One stroke	---	Third funnel had a stroke of lightning over the top of its juncture with the cloud and *appeared to break into pieces* 10-15 sec later.
18	Cdr. N. P. Carr S2E; VS-31	34/105°	8-20-67	0744-	U	360	U	U	U	U	U	U	---	None	~0.25γ	A second spout formed nearby. Magnetic anomaly occurred on one pass only.
19	Lcdr. C. Holland CGC ARIADNE	123/121°	8-21-67	0650-0658	>8	300	U	>5	20	75	38	U	---	None	---	
20-21	---------do---------	100/120°	8-21-67	0815-0822 0853-0858	7 5	300	U	>5	20	210	64	U	---		---	First funnel descended to 3/4 way to water and stopped descent. A short while later spray was generated at surface and formed a sheath that grew from surface to cloud. Process reversed as spout quit.
22	Cdr. N. P. Carr S2E; VS-31	114/090°	8-27-67	0821-	U	360	U	U	10	360	84	A[3]	---		<0.1γ	Flew through spout once; slight bump.
23	---------do---------	111/090°	8-27-67	0836-	U	330	U	U	10	80	40	U	---			Flew through spout twice.
24	---------do---------	237/089°	9-5-67	1250-	U	540	U	U	6	140	52	A	---			Cup shaped vortex at surface.
25	Cdr. Bullard S2E; VS-31	212/061°	9-10-67	1030-	U	360	U	U	3	360	84	U	---			

[1]U, unknown
[2]C, cyclonic
[3]A, anticyclonic

TABLE 1.- TABULATION OF ENCOUNTERS WITH ATMOSPHERIC VORTICES - Continued

Event	Commanding officer	Location from Key West miles/direction	Date	Time: EDT	Duration, min	Cloud: Altitude of cloud base, m	Cloud: Top of cell or cloud, m	Cloud: Maximum width of cloud, miles	Funnel: Diameter, m	Funnel: Length down from cloud, m	Funnel: Inferred minimum wind velocity in vortex, m/s	Funnel: Direction of rotation	Electrical: Maximum intensity within 2 miles of spout	Electrical: Lightning during funnel life	Electrical: Maximum identifiable magnetic anomaly, γ	Comments
26	Ground observation	5/090°	6-11-68	1520-1530	10	450	3000	5	10	450	94	U	---	None	---	During last part of funnel life, it made 4 right-angle turns between cloud and surface.
27	---------do---------	12/270°	6-16-68	1720-1735	15	450	U	>5	10	45	30	U	---		---	Funnel appeared to be at edge of cloud. Demise came about as funnel diameter enlarged about 25 percent and dissipated, suggesting updraft or suction in center was stopped.
28-35	---------do---------	~8/180°	6-17-68	0848-0920	10 ea. one 30	300	U	>5	10-30	300	77	U	---		--	Third funnel to form lasted 30 min, and was ~30 m in diameter. Cloud tops are very low as seen in figure 17.
36-37	---------do---------	4/270°	6-18-68	0930-0935	2 or 3 after sighting	300	U	U	10		20-60	U	---		---	Rainshower between spouts spread out, enveloped them, and probably caused their demise.
38	Cdr. N. P. Carr S2D; VX-1	20/235°	6-18-68	1338-1400	22	480	3000	4	12	400	90	C	---	Perhaps 1 stroke	0.1γ on one pass	Anomaly may be due to updraft. Lightning stroke in area indicated by MAD gear may have been an adjustment in electrical gear aboard aircraft.
39	Cdr. N. P. Carr S2D; VX-1	12/180°	6-18-68	1435-1440	5	350	U	U	10	30	24	U	---	None	0.05γ on one pass; 0.1γ on two passes	Anomalies observed may have been due to updrafts near funnel.
40	Cdr. R. V. Wilson S2D; VX-1		6-20-68	1512-1520	8	600	U	U	10	120	49	C	---		<0.05γ	Spout merged with rain.
41	---------do---------	Between Key West and Marathon	--do---	1533-1545	12	600	U	U	10	100	44	C	---			
42	---------do---------		--do---	1600-1610	10	600	U	U	10	600	109	C	---			
43	---------do---------		--do---	1607-	U	600	U	U	10	60	35	C	---			
44	---------do---------		--do---	1607-	U	600	U	U	10	150	55	A	---			
45	---------do---------		--do---	1627-1634	7	600	U	U	10	100	44	U	---			Spout rained out.
46-48	Ground observation	~3/340°	6-21-68	0730	~5 ea.	~400	U	U	~10	100	44	U	---	---	---	
49	Cdr. N. P. Carr S2E; VX-1	91/300°	7-8-68	1522-1540	18	530	U	U	12	530	102	A	<100 V/m	None	<0.05γ	Aircraft was charged to about 5000 V by rain.
50	---------do---------	91/300°	7-8-68	1542-1545	3	440	U	U	10	60	35	U				
51	Lt. J. J. Drew S2E; VX-1	53/317°	7-9-68	1601-1612	11	540	3000	U	8	540	104	C				Filament to surface but funnel only 20 percent of the way down.
52	---------do---------	53/317°	7-9-68	1615-1620	5	540	U	U	8	540	104	U				Do.
53	Lcdr. G. E. McArthur S2E; VX-1	28/250°	7-18-68	1530-1539	9	400	2400	3	10	40	28	A				Funnel was larger at top but pattern on water was estimated at 10 m. Rain followed withdrawal of spouts.
54	---------do---------	45/330°	7-18-68	1621-1631	10	480	2700	3	10	100	44	C				Do.
55	---------do---------	45/330°	7-18-68	~1621	U	480	2700	3	10	None	U	C				No funnel was found but vortex was visible on water and yawed aircraft as we flew through.

TABLE 1.- TABULATION OF ENCOUNTERS WITH ATMOSPHERIC VORTICES - Continued

						Cloud			Funnel				Electrical			Comments
Event	Commanding officer	Location from Key West miles/direction	Date	Time: EDT	Duration, min	Altitude of cloud base, m	Top of cell or cloud, m	Maximum width of cloud, miles	Diameter, m	Length down from cloud, m	Inferred minimum wind velocity in vortex, m/s	Direction of rotation	Maximum intensity within 2 miles of spout	Lightning during funnel life	Maximum identifiable magnetic anomaly, γ	
56	Lcdr. R. N. Beasley S2E; VX-1	55/060°	7-19-68	1509-1515	6	540	U	U	10	20	17	A	2500 V/m in cloud	1 or 2 strokes	<0.05γ	Believe charges and lightning associated with other clouds.
57	Ground observation	4/030°	7-21-68	1225-1235	10	~500	~2500	U	10	500	100	U	---	None	---	Spout merged with rain and disappeared.
58	Lcdr. R. H. Beasley S2E; VX-1	77/290°	7-26-68	1420-1446	26	480	2200	2	10	120	49	C	<100 V/m		<0.05γ	Spout withdrew as it merged with rain.
59	Lcdr. K. E. Earhart S2E; VX-1	30/150°	7-29-68	1402-1415	13	490	3000	5	50	100	44	C				Nice profiles of aircraft charging due to rain; see figure 22(a).
60	Cdr. N. P. Carr S2E; VX-1		8-1-68	0948-0959	11	480	U	>10	10	60	35	U	<100 V/m	None	<0.05γ	All spouts withdrew as they merged with light rainfall nearby.
61	--------do----------		8-1-68	0959-1020	21	540	U	>10	6	100	44	C				
62	--------do----------		8-1-68	1028-	U	540	U	>10	15	30	24	U				
63	--------do----------	~1-5 miles north of Keys between Key West 20/060° and Marathon	8-1-68	1054-1106	12	540	U	>10	15	60	35	C				Smoke flares yielded good circulation pattern; see figure 14.
64	--------do----------		8-1-68	1114-1121	7	540	U	>10	6	60	35	U				
65	--------do----------		8-1-68	1123-	U	540	U	>10	15	30	24	U				
66	--------do----------		8-1-68	1140-1145	5	540	U	>10	15	100	44	U				
67	--------do----------		8-1-68	1145-	U	540	U	>10	15	100	44	U				
68	Cdr. R. V. Wilson S2E; VX-1	22/350°	8-2-68	0807-0820	13	700	3000	>5	6	700	117	U	<100 V/m	None	<0.05γ	Spouts withdrew as merged with rain.
69	--------do----------	20/350°	8-2-68	0808-0824	16	5-600	3000	>5	6	500	100	C				Do.
70	Lcdr. K. E. Earhart S2E; VX-1	85/085°	8-7-68	0823-0825 0833-0836	Believe to be same spt. ~13 min	600	3000	>5	6	100	44	U				Spout withdrew and then reappeared 8 min later.
71-76	Ground observation	5/000°	8-8-68	1350-1530	~15 ea.	~500	Max. cloud in area at ~10,000 m	>20	10-50	200-500	63-100	U				Spouts seen in sequence from fishing boat, at end of large cloud complex. Lightning in cells with anvils but not near spouts.
77	Lt. J. F. Fitzgerald S2E; VX-1	23/250°	8-9-68	1230-1242	12	540	U	3	10	50	30	A			<0.1	
78	Lcdr. R. W. Case S2E; VX-1	30/030°	8-12-68	1438-1446	8	400	U	U	6	40	28	A	100,000	Stroke every 40-60 sec	<0.1	Uncertain whether electricity with cloud over funnel or with another cloud. Many large clouds close together in that area - some to ~8000 m. Temperature pause at 6000 ft.

TABLE 1.- TABULATION OF ENCOUNTERS WITH ATMOSPHERIC VORTICES - Concluded

Event	Commanding officer	Location from Key West miles/direction	Date	Time: EDT	Duration, min	Cloud: Altitude of cloud base, m	Cloud: Top of cell or cloud, m	Cloud: Maximum width of cloud, miles	Funnel: Diameter, m	Funnel: Length down from cloud, m	Funnel: Inferred *minimum* wind velocity in vortex, m/s	Funnel: Direction of rotation	Electrical: Maximum intensity within 2 miles of spout	Electrical: Lightning during funnel life	Electrical: Maximum identifiable magnetic anomaly, γ	Comments
79	Ground observation	~5/000°	8-13-68	1555-1605	10	~500	~2400	U	~10	~200	63	U				Nicely shaped funnel about 40 percent down.
80	Lcdr. R. H. Beasley S2E; VX-1	21/320°	8-14-68	1636-1642	6	600	U	U	20	100	44	C	<100 V/m	None	<0.2	Pattern on water very clearly defined as a ring of disturbed water with calm water in center.
81	Cdr. R. V. Wilson S2E; VX-1	64/310°	8-19-68	1431-1435	4	600	3300	5	12	30	24	U				Temperature pause at 7000 ft.
82	---------do---------	48/315°	8-20-68	1510-1515	5	600	10,000	>8	10	0	~80 by spray	A	30 kV/m	Occasional		Water devil occurred with a large storm cloud. Water spray generated went over half way to cloud from water but no detectable funnel.
83-86	Ground observation	~5/000°	8-20-68	1810-1830	5 ea.	450	600	~3	~20	100-150	44-55	U				Very low clouds over funnels had soft tops that did not grow or billow out until spouts had withdrawn. No rain.
87	---------do---------	*By* Sand Key	8-21-68	1150-1229	39	600	2700	3	30	600	108	U				Funnel located by Gerald Clemons of ESSA Int. Airport; arrived at cloud after spout quit and found no E or B present in parent cloud.
88	Lt. J. F. Fitzgerald S2E; VX-1	55/330°	8-26-68	1610-1625	5	550	2000	U	6	500	100	C	2500 V/m	None	<0.1	Heavy rain in cloud one-half hour after spouts quit.
89	---------do---------	55/330°	8-26-68	1610-1625	5	550	2000	U	6	100	44	C				Do.
90	---------do---------	13/060°	8-27-68	1435-1439	7	600	U	U	6	U	U	U	400 V/m centered 1 min away			Funnel appeared to touch down on a Key.
91	---------do---------	21/230°	8-27-68	1546-1556	10	630	U	U	6	420	91	C	100 V/m		<0.05	Pattern on water was about twice as large as funnel diameter which is typical of a number of the observations.
92	---------do---------	2/000°	8-27-68	1610-1622	12	540	U	U	10	360	85	C	20 kV/m ~1 min east of spout	1 stroke every 5 sec	<0.2	Believe electricity to be associated with clouds nearby.
93	---------do---------	31/235°	8-27-68	1658-1710	12	660	U	U	6	30	24	C	3-400 V/m 10 sec south of spout	None	<0.1	These two events were ~5 flight seconds or ~300 m apart.
94	---------do---------	31/235°	8-27-68	1700-1713	13	660	U	U	6	30	24	U			<0.1	
95	Lt. J. F. Fitzgerald S2E; VX-1	17/180°	8-29-68	~1100	U	>6000	None	None	6	0	U	C	None	None	None	Water devil occurred on a day when only clouds were some thin cirrus at about 6000 m.
96	---------do---------	15/000°	9-9-68	1745-1753	8	600	2400	U	U	U	U	C	<500 V/m		<0.1	Scale set at 30 kV so voltage is noise level.
97	Lcdr. R. W. Case S2E; VX-1	20/089°	9-17-68	1422-1429	7	375	2100	>2	12	30	24	C	<100 V/m			
98	---------do---------	32/266°	9-17-68	1542-1545	3	600	U	U	U	0	U	U	<400 V/m			Pattern on water but no visible funnel.
99	Lcdr. R. H. Beasley S2E; VX-1	20/090°	9-19-68	1723-1725	2	480	U	>3	6	90	43	C	<100 V/m			
100	Ground observation	~10/090°	9-24-68	0825-0839	14	300	2700	>5	30	250	70	U	U		U	Spout seen from NAS ramp. Funnel was large and went to surface.
101-4	Lt. J. J. Drew S2E; VX-1	~22/270°	9-30-68	0800-0845	~10 ea.	450-500	~3000	U	~10	100-250	44-70	4C	<100 V/m		<0.1	

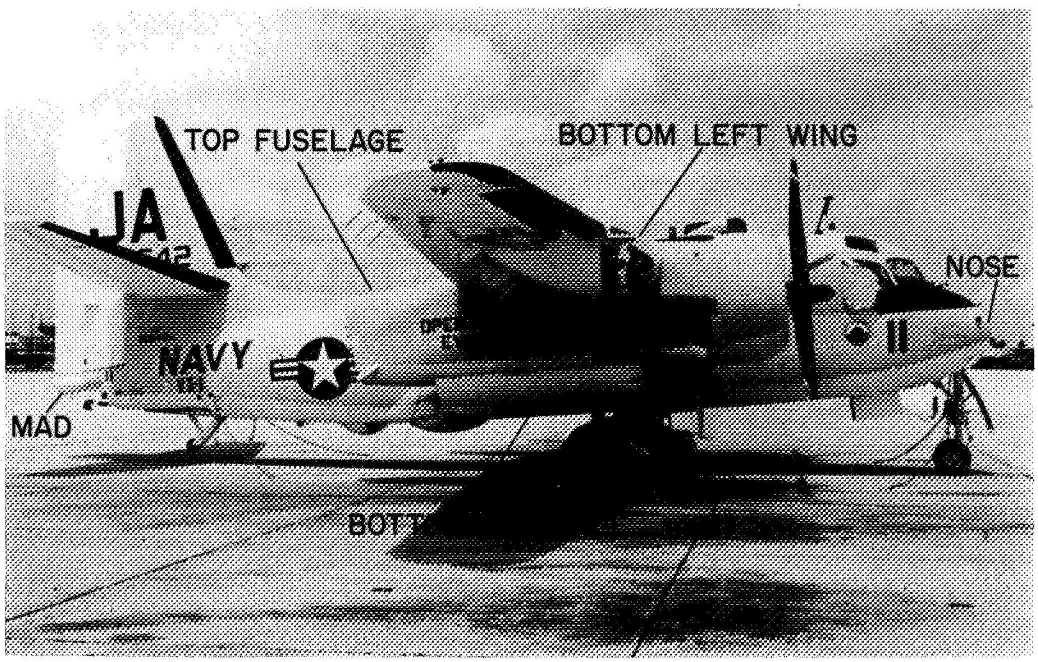


Figure 1.- Grumman S2E aircraft of Navy Air Development Squadron 1 used in 1968 measurements. Four electric field sensors located as indicated. Magnetic-anomaly detector (MAD) boom in retracted position; extended position is 16 ft farther behind aircraft.

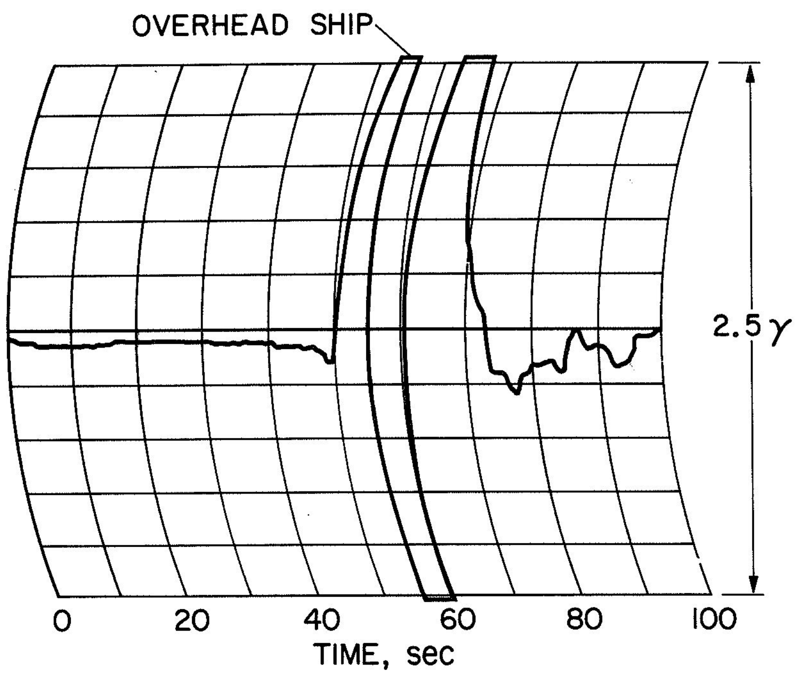
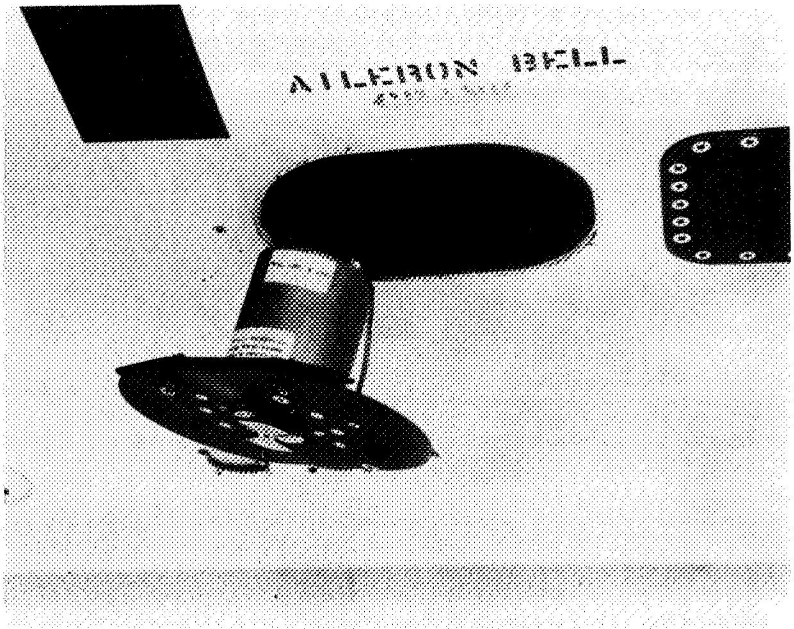
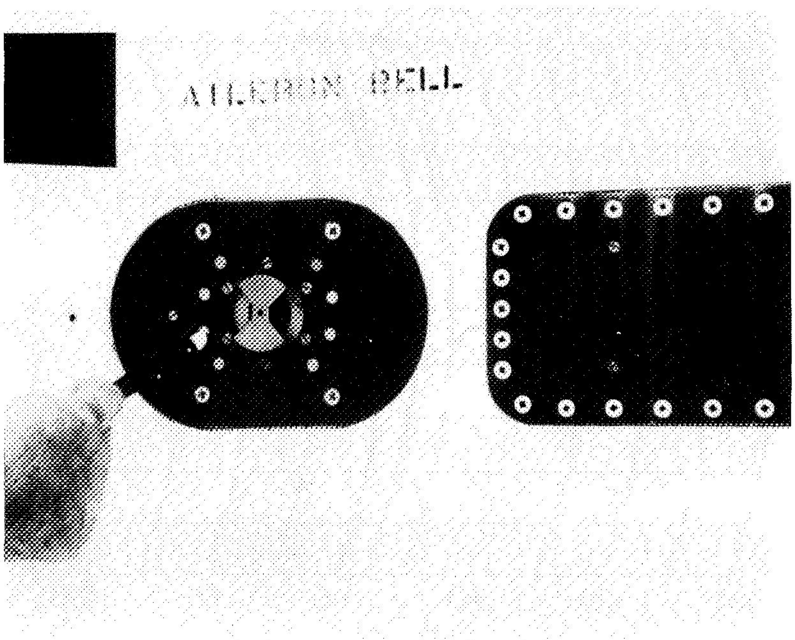


Figure 2.- MAD tape record of noise level and a magnetic anomaly caused by merchant ship (scale 2.5 γ). Noise on record after encounter requires about 0.5 min to recover initial level. Taken over Atlantic at 1000-ft altitude, 1315 EDT.



(a) Entire sensor unit exposed.



(b) Flush mounting ready for flight.

Figure 3.- Electrometer installation on underside of left wing.

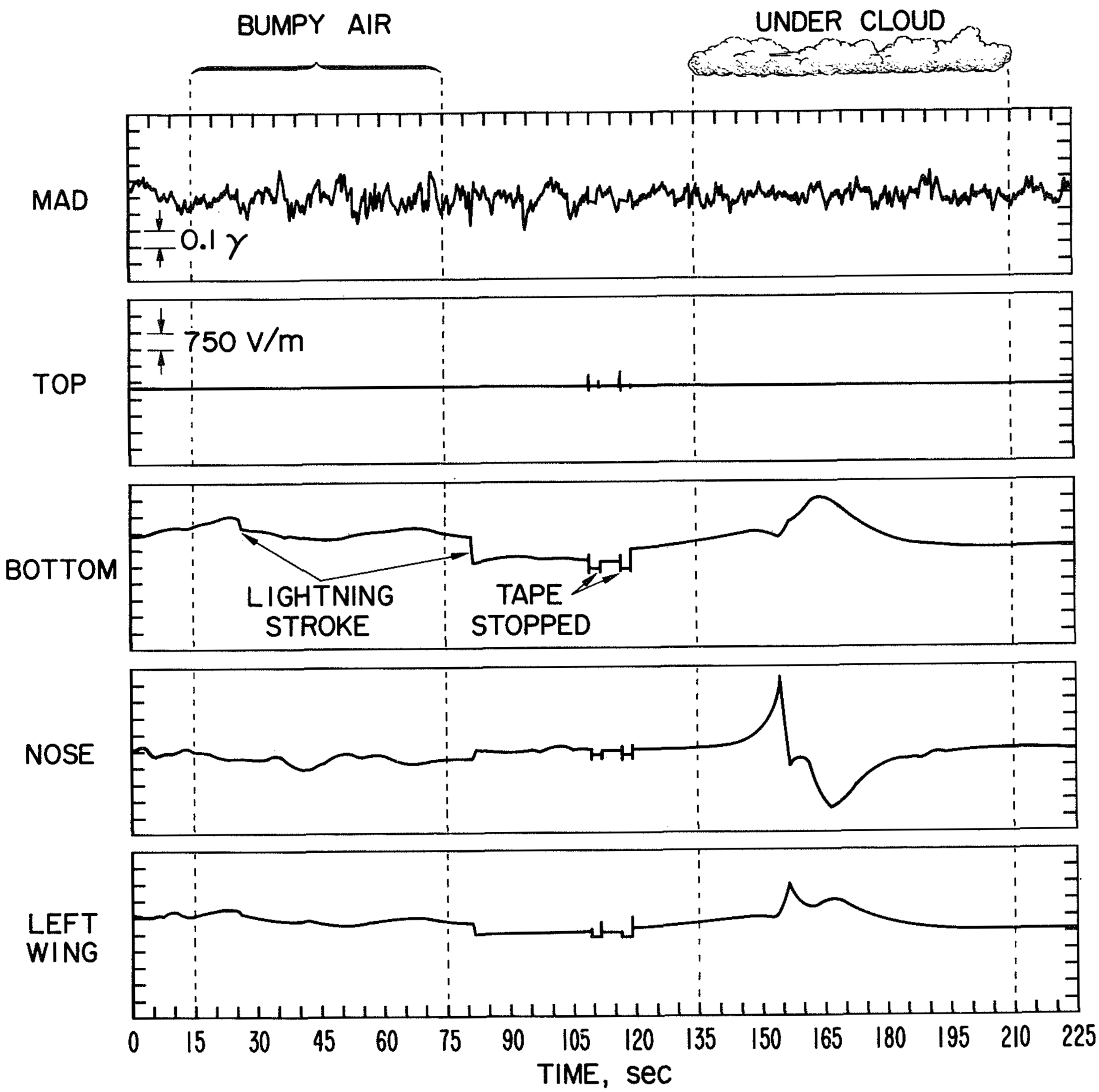
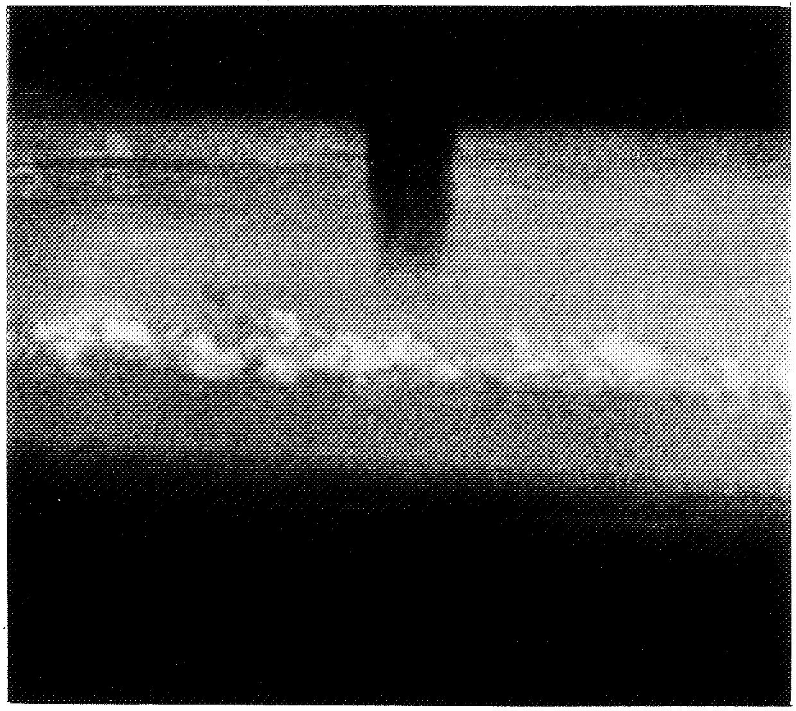


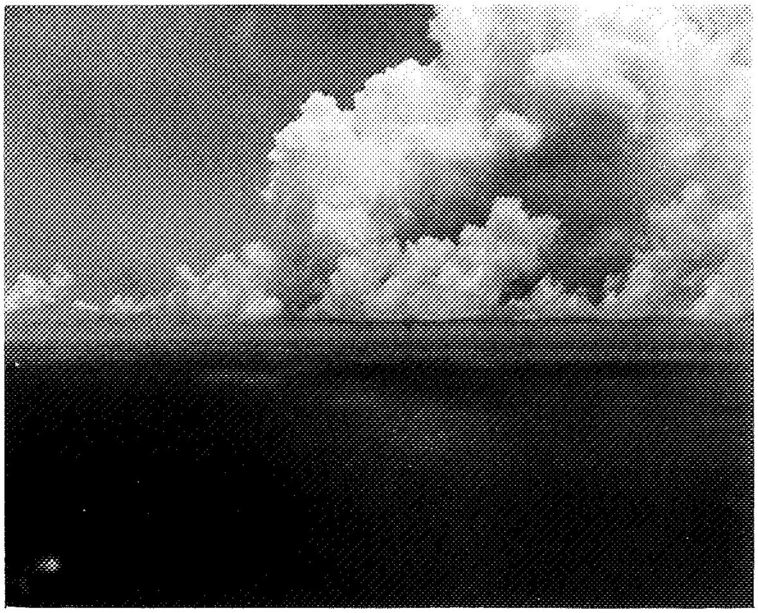
Figure 4.- Record of electric field under and around clouds containing electrical activity. Tape speed = 1 mm/s. Scale 1 mm = 150 V/m. 1450 EDT, 19 July 1968. Note discontinuity in records when lightning occurred and note rapidly changing signal under cloud. (Top sensor was not active because rain water had entered it.)



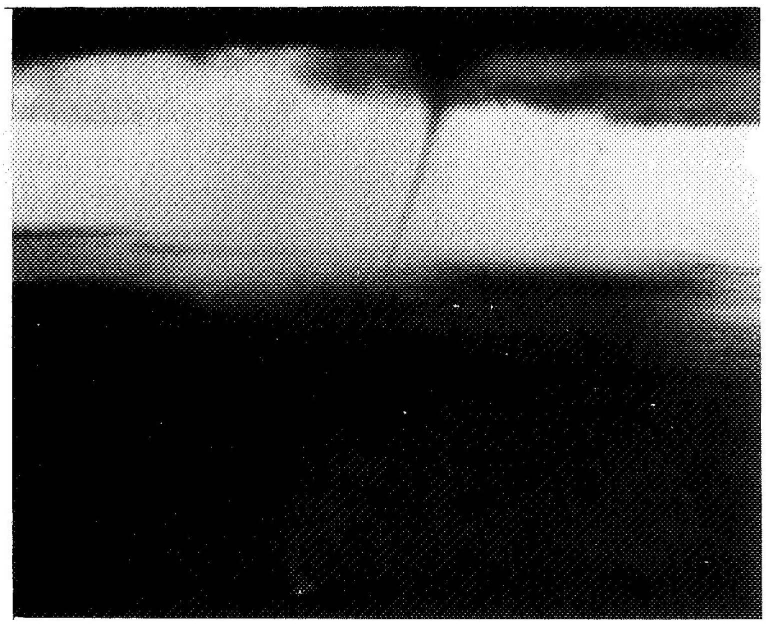
(a) 1615 EDT, 9 July 1968.

(b) 1330 EDT, 9 June 1967.

Figure 5.- Funnels during early stages of formation as they protrude from cloud base, illustrating square lower end and transparent core.



(a) Parent cloud and funnel. Note similarity of left-hand portion of cloud to tornado cloud in figure 12.

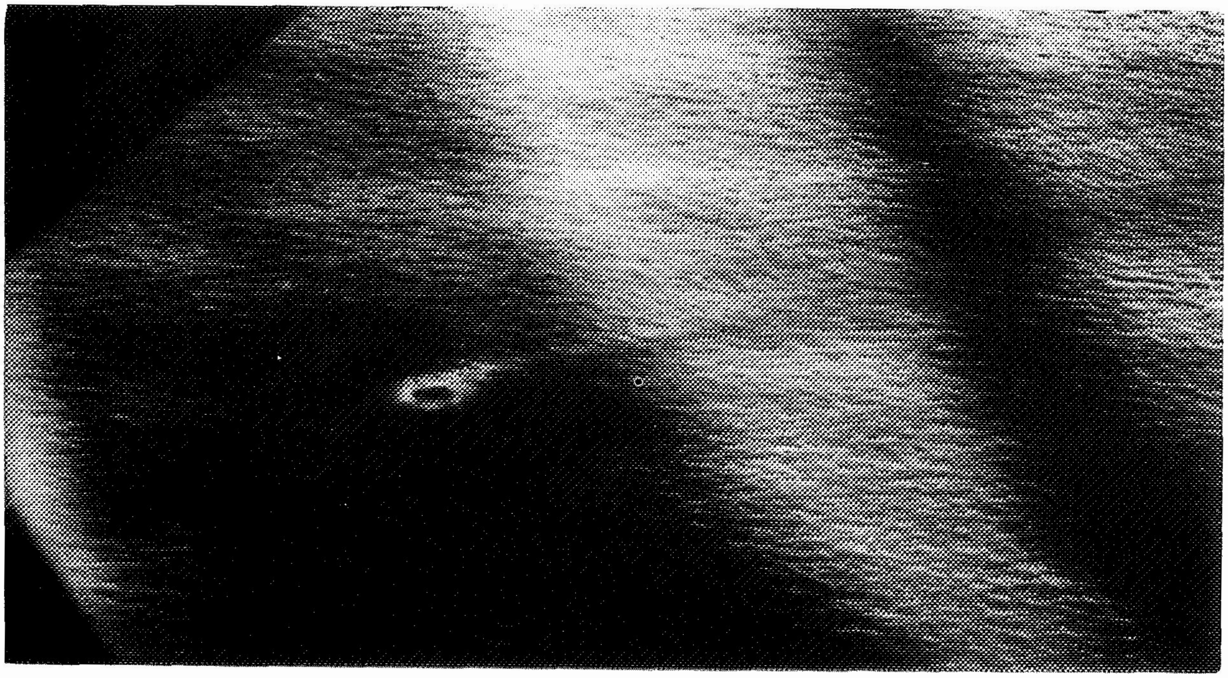


(b) Funnel beneath cloud, and spray at surface.

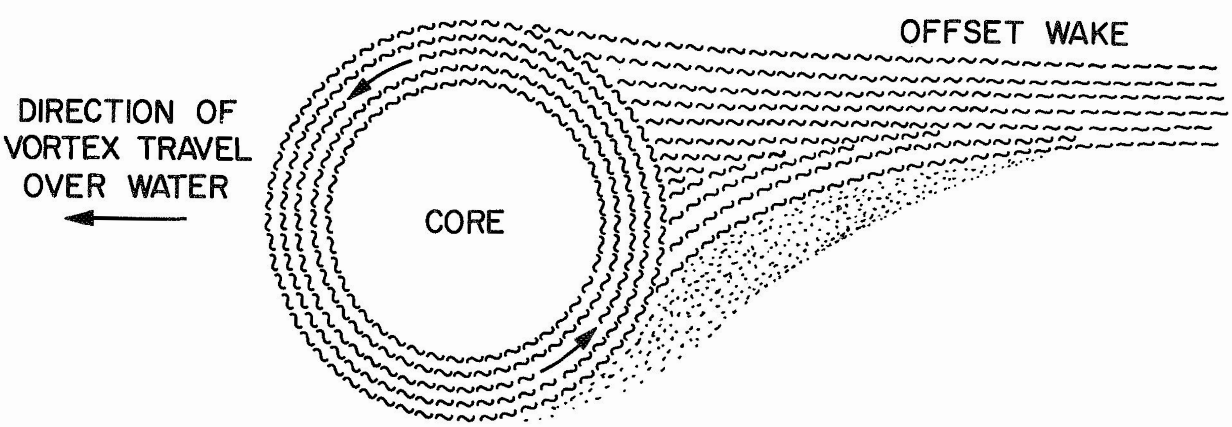
Figure 6.- Typical parent cloud and waterspout with funnel extending more than 80 percent of the distance from cloud to water surface. Spray from vortex at surface rises at least one-third of the way to cloud. 1338-1400 EDT, 18 June 1968. Cloud base 1600 ft, cyclonic rotation. Wind velocity in funnel $\gtrsim$ 90 m/s. Intensity decreased as spout merged into rain shower.

(c) Vortex at water surface showing spray column and offset of wake due to cyclonic rotation. A calm center or eye does not appear to be present in this event (cf. fig. 7).

Figure 6.- Concluded.

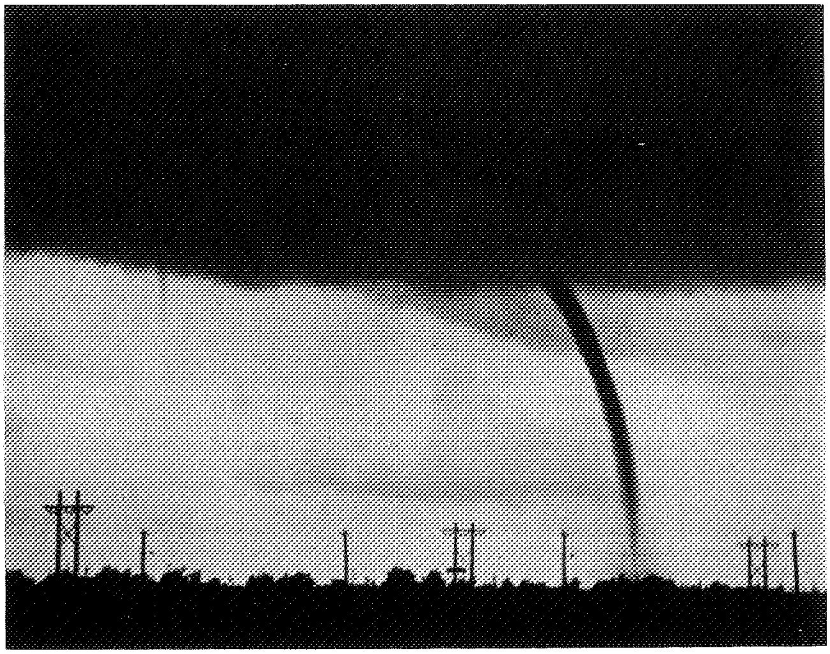


(a) Cyclonic vortex pattern on water showing offset wake and relatively calm center or eye of vortex. Many spouts have quiet centers during the early stages of funnel life. 1000 EDT, 9 June 1967, wind velocity in vortex ≳ 56 m/s.

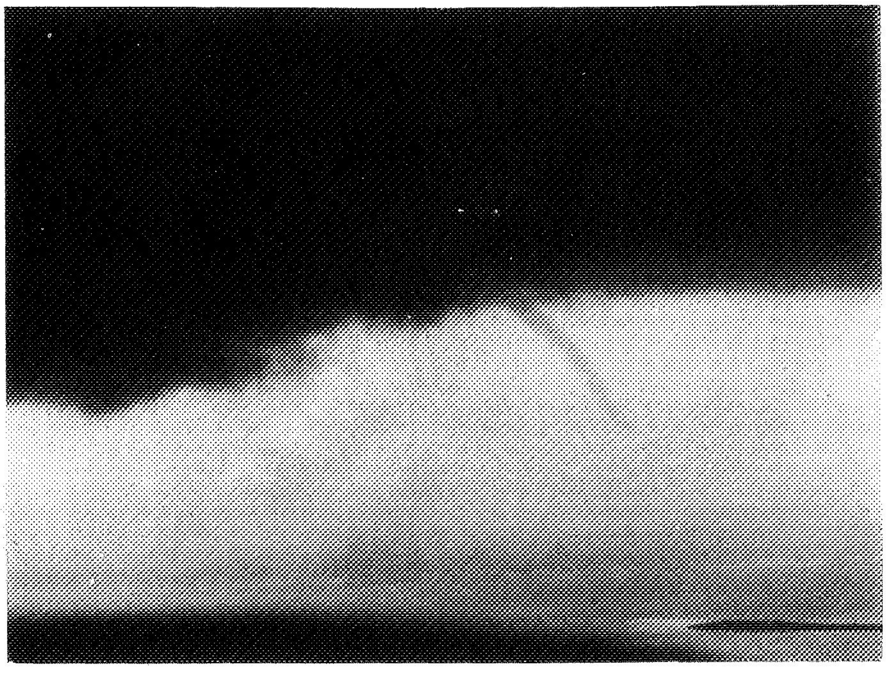


(b) Sketch of flow field of vortex interaction with sea surface.

Figure 7.- Identification of direction of rotation by offset of vortex wake.



(a) Photograph taken near Key West, 27 Aug. 1968 (by E. E. Adams, AXC of VX-1). Funnel touches water beyond highway and houses in foreground. Note second funnel to left of and behind the larger event. Aircraft was studying five other spouts about 30 miles away when this event occurred.



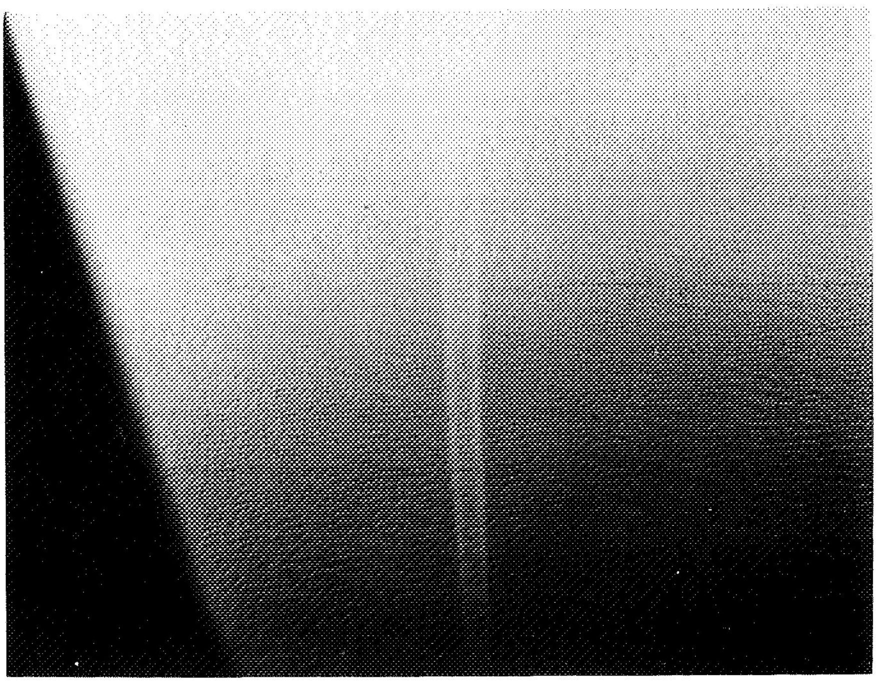
(b) Slanted and curved funnel showing juncture with cloud base. 1700 EDT, 27 Aug. 1968.

Figure 8.- Examples of the curvature of a funnel axis.

(c) View down funnel to vortex and wake on water. 1522-1540 EDT, 8 July 1968. Wind velocity in funnel $\geq$ 102 m/s. Note shadow of edge of cloud and offset of wake due to anticyclonic rotation.

Figure 8.- Concluded.

(a) Contact of funnel having hollow core with cloud base. No additional stratification detectable in contrast with figure 10. 1522-1540 EDT, 8 July 1968. Wind velocity in funnel ≳ 102 m/s.



(b) View of translucent midsection of typical small event (~3 m diam. at this section, cyclonic rotation). Wave pattern on water visible through funnel. 1601-1612 EDT, 9 July 1968. Wind velocity in funnel ≥ 100 m/s.

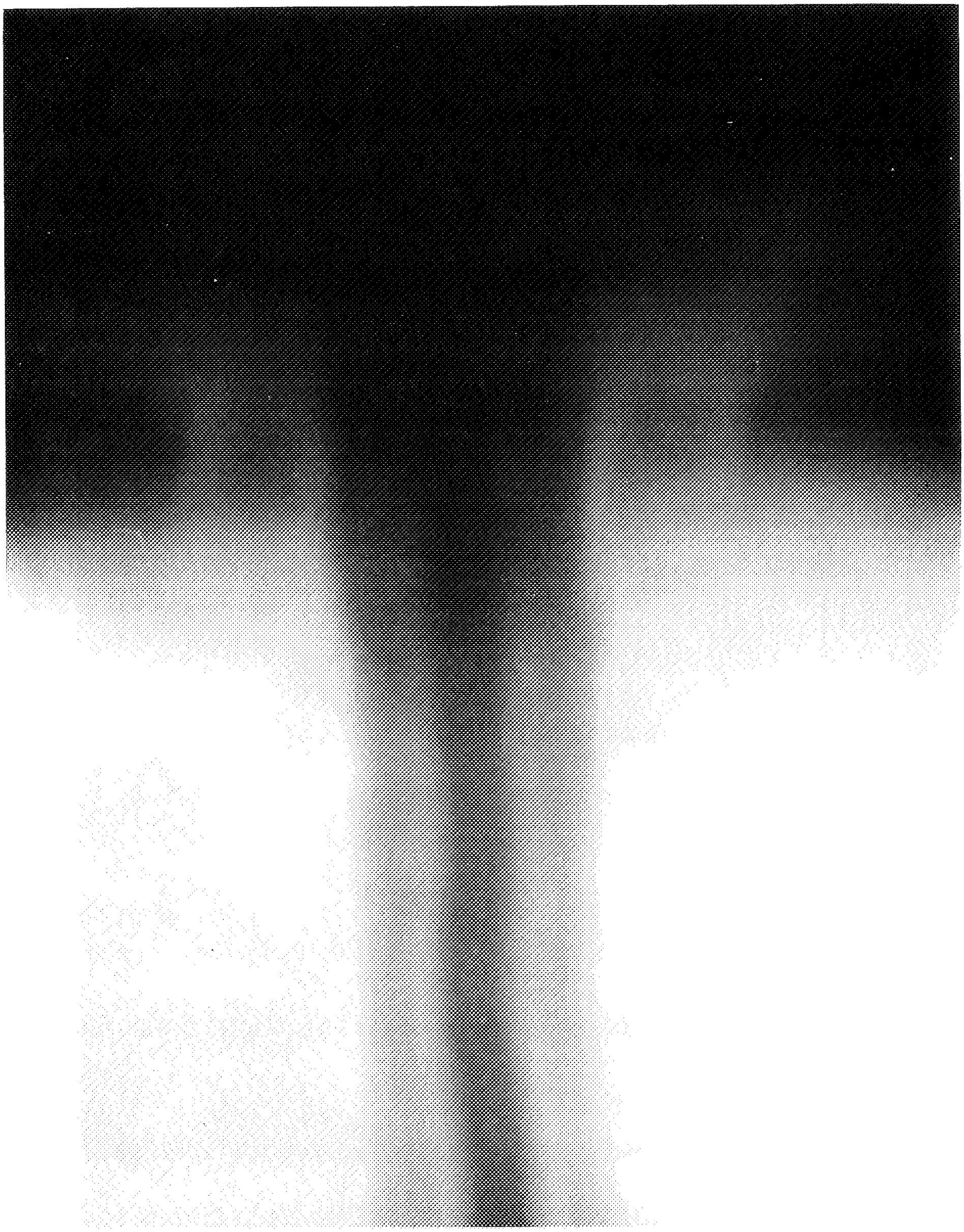
Figure 9.- Examples of cylindrical stratification of funnels.

(a) First photo of funnel with wing tip of P2V.

Figure 10.- Most intense vortex observed during 2 year period (estimate that at least 5-10 similar events occurred in the Key West area when project aircraft was not available). Note cylindrical stratification of spray and condensation droplets in funnel indicating a high degree of organization; cyclonic rotation. Turbulence appears to be restricted to layer near water surface. 1000 EDT, 7 June 1967, cloud base at 1000 ft, cloud top ~10,000 ft. Wind velocity in funnel $\gtrsim$ 77 m/s. Pilot noted some lightning and interference on single side-band radio. MAD recorder (AN/ASQ-8) oscillated rapidly between stops on 1 γ scale while P2V was under cloud.

(b) Early stage of funnel contact with water.

Figure 10.- Continued.



(c) Cylindrical stratification of spray and funnel at surface.

Figure 10.- Continued.

(d) Funnel midsection during intense phase.

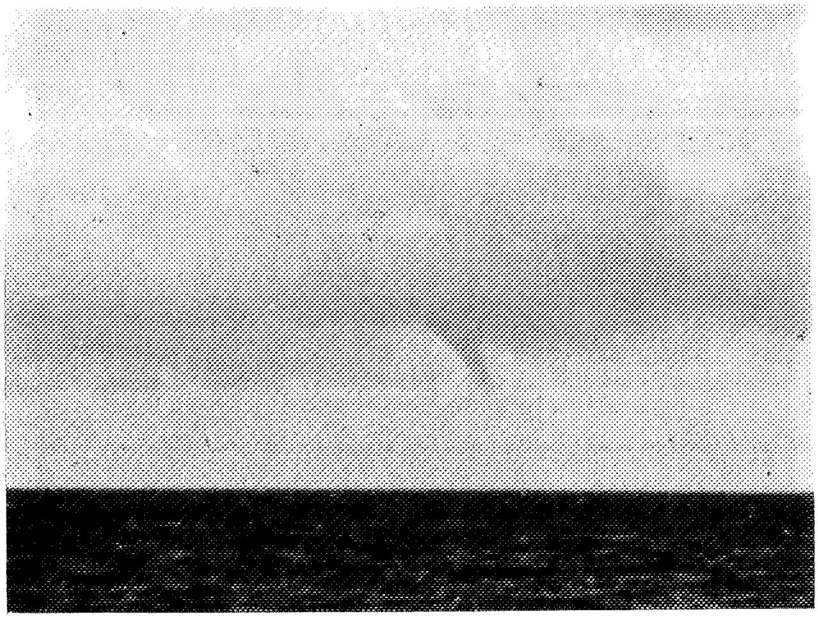
Figure 10.- Continued.

(e) Structure of funnel where it enters cloud base.

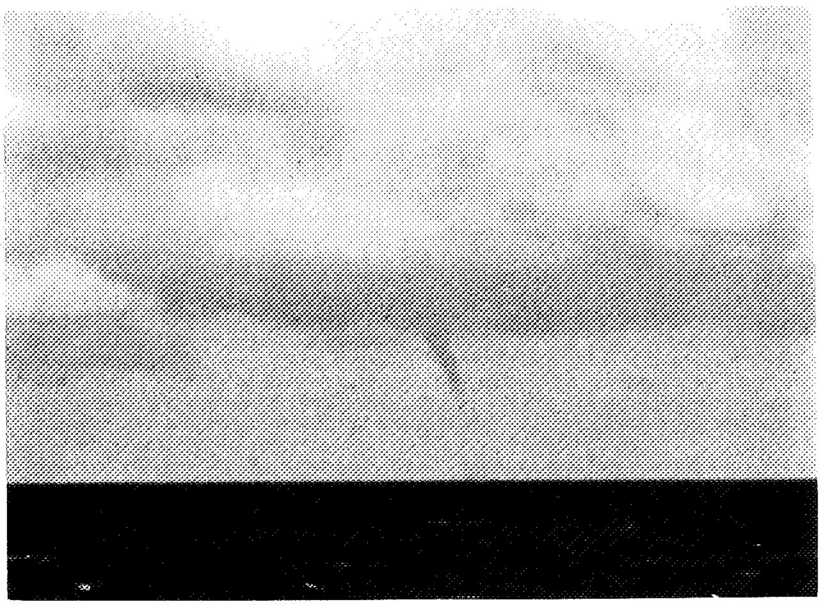
Figure 10.- Continued.

(f) Later stage of funnel and spray at surface.

Figure 10.- Concluded.

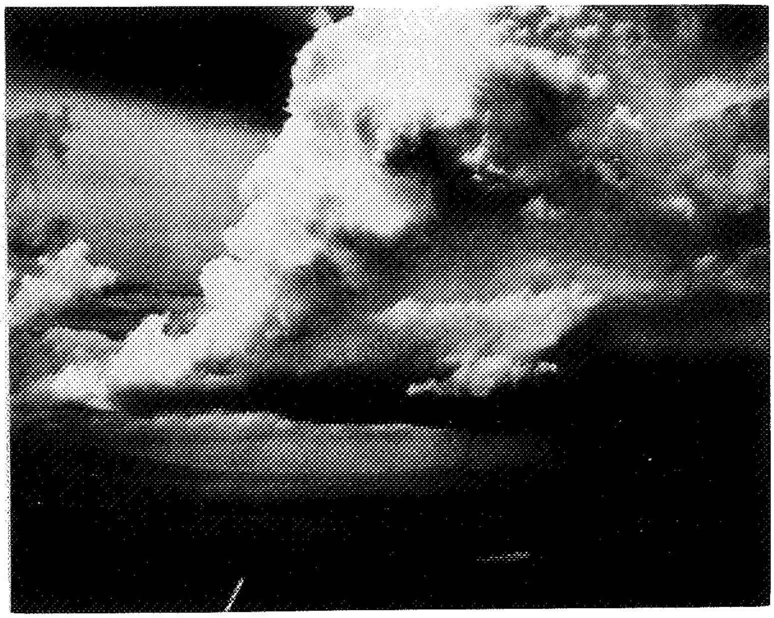


(a) Initial stages of funnel formation.

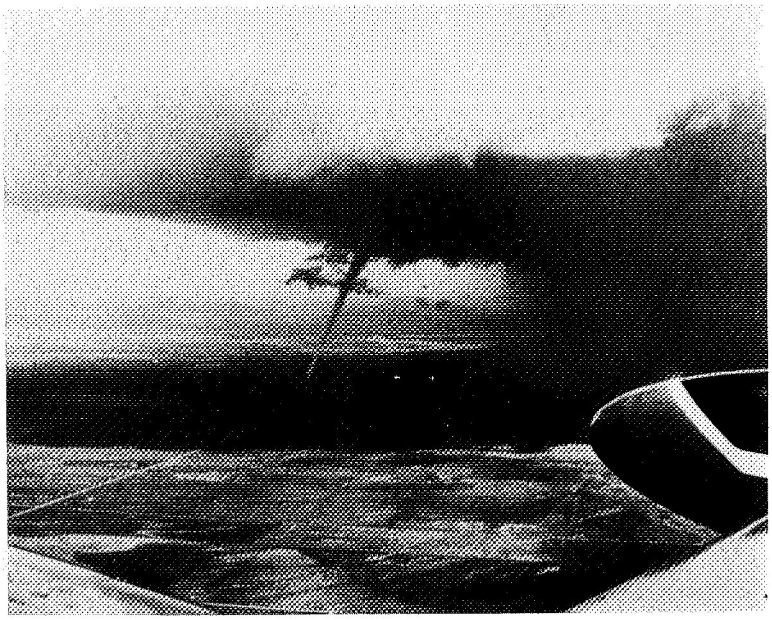


(b) Final stages of funnel existence.

Figure 11.- Funnel extended from cloud base to about 80 percent of distance to water and then stopped. A few seconds later water spray was generated at surface which rose as a cylindrical sheath around funnel up to cloud base. Spray then fell to surface and funnel withdrew into cloud. 0815-0822 EDT, 21 Aug. 1967.



(a) Cell over funnel when first observed.



(b) Vortex during most intense phase.

Figure 12.- Tornado and parent cloud similar in appearance to waterspout cloud in figure 6(a). Picture taken shortly after 1442 MDT, 24 July 1965, near Westcliff, Colorado, by Jim Bradford, Bill TenBroek, and Carl Heinen of Systems and Research Div., Honeywell, Inc., St. Paul, Minn. Valley floor 8,000 ft, aircraft altitude 9,500 ft, cloud base 10,000 ft, and top of cloud cell ~20,000 ft (i.e., 12,000 ft above the ground). Funnel diameter at cloud base ≈170 ft. Funnel withdrew and hail followed. Wind velocity in funnel ≳ 109 m/s.

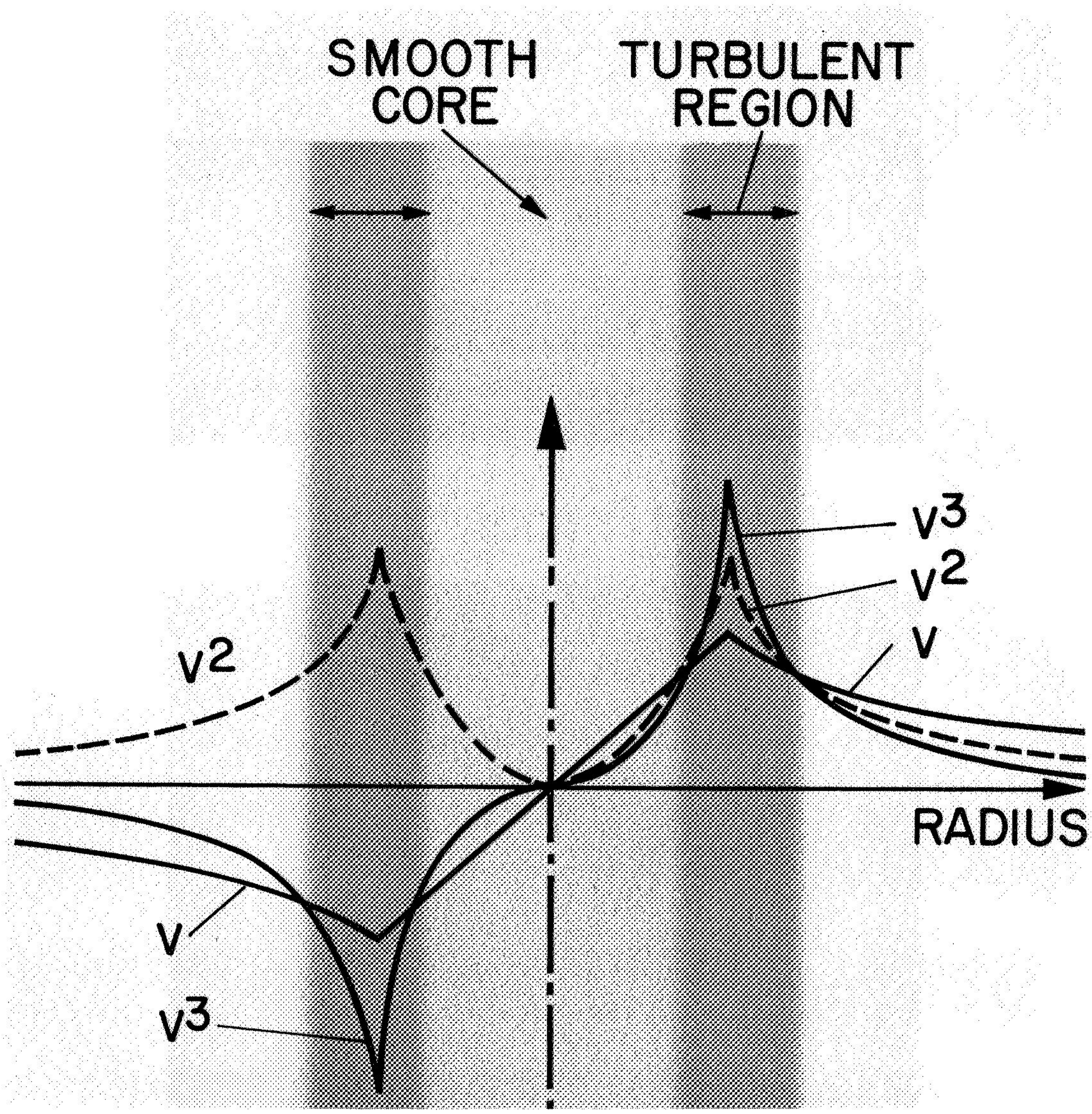
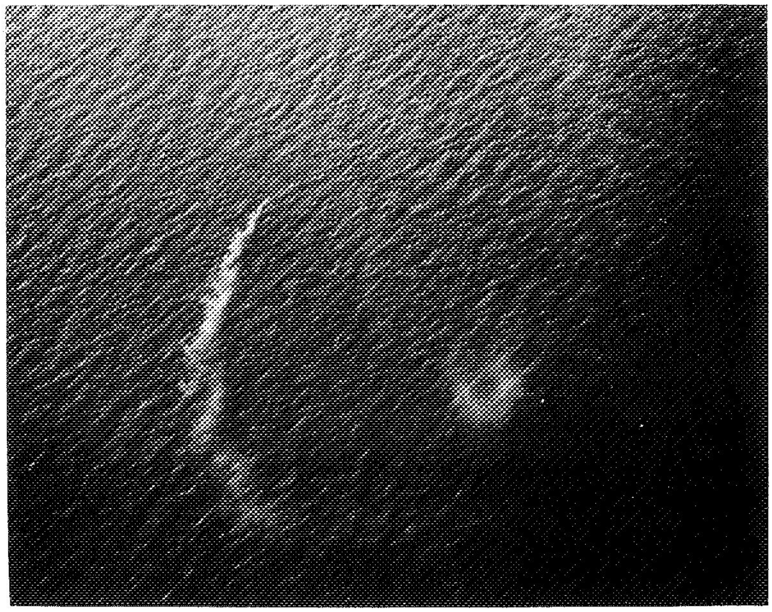


Figure 13.- Qualitative dependence of velocity, v, dynamic pressure, $(\rho/2)v^2$, and work capability, $v(\rho/2)v^2$, on radius for a vortex. Low energy of air near axis produces smooth core and a turbulent ring on water surface as shown in figures.

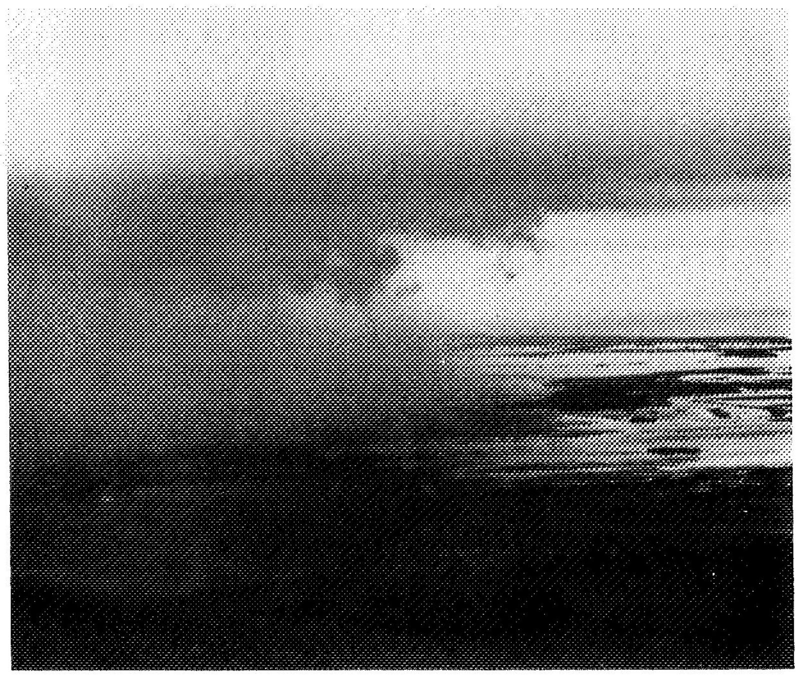


(a) Overall view of smoke flare near vortex-water contact point.

(b) Close-up view of smoke entering vortex.

Figure 14.- Smoke pattern around the contact point of vortex with water surface. Note that vortex flow field is much larger than the active region indicated by agitated water and funnel. Smoke formed a cup-shaped figure (with a small quiet center) ~10-m diam. and 30 m high, cyclonic rotation. 1054-1106 EDT, 1 Aug. 1968. Cloud base 1800 ft, wind velocity in funnel $\gtrsim$ 60 m/s.

(a) Spout well formed and away from rain.



(b) Spout merging with rain.

Figure 15.- Photographs of a funnel next to rainshower which overtakes and encompasses it. 1546-1556 EDT, 27 Aug. 1968.

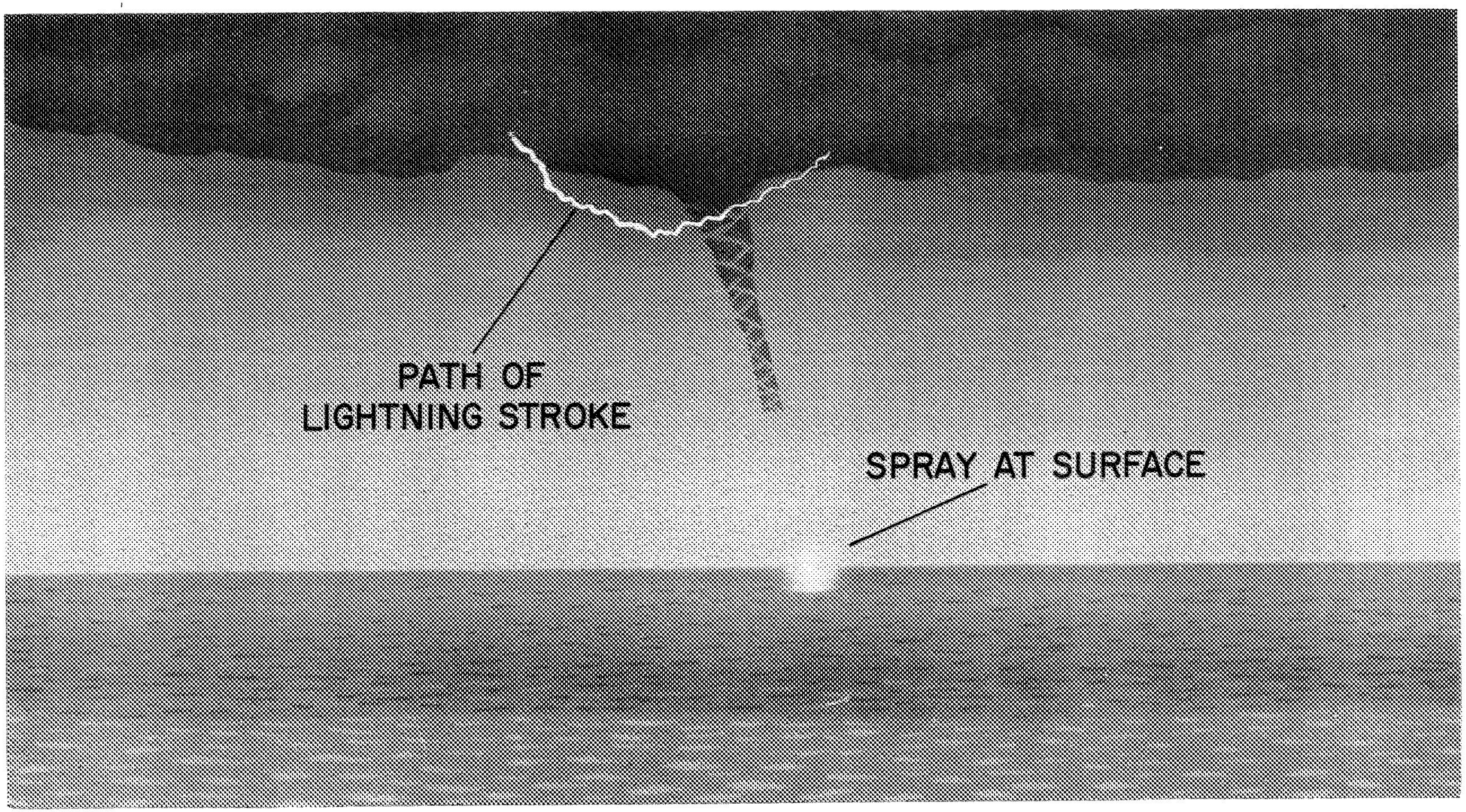
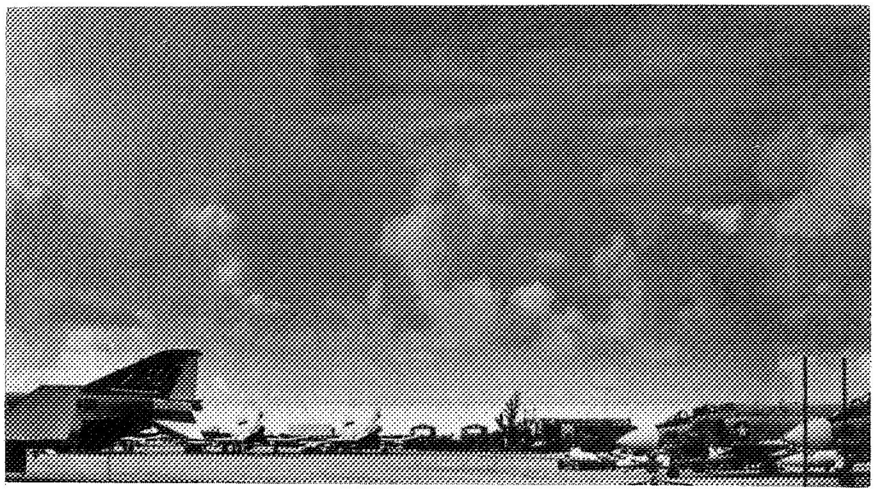
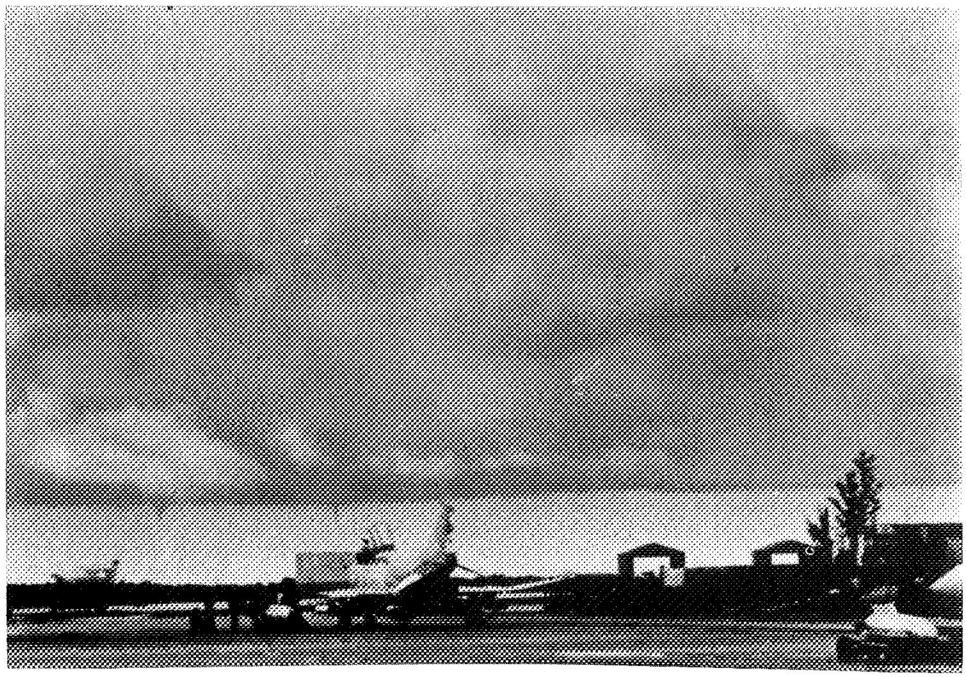


Figure 16.- Sketch of lightning demise of funnel. 1630 EDT, 9 Aug. 1967. Seams in funnel appeared about one-half minute after stroke occurred and pieces drifted apart as they evaporated from view.

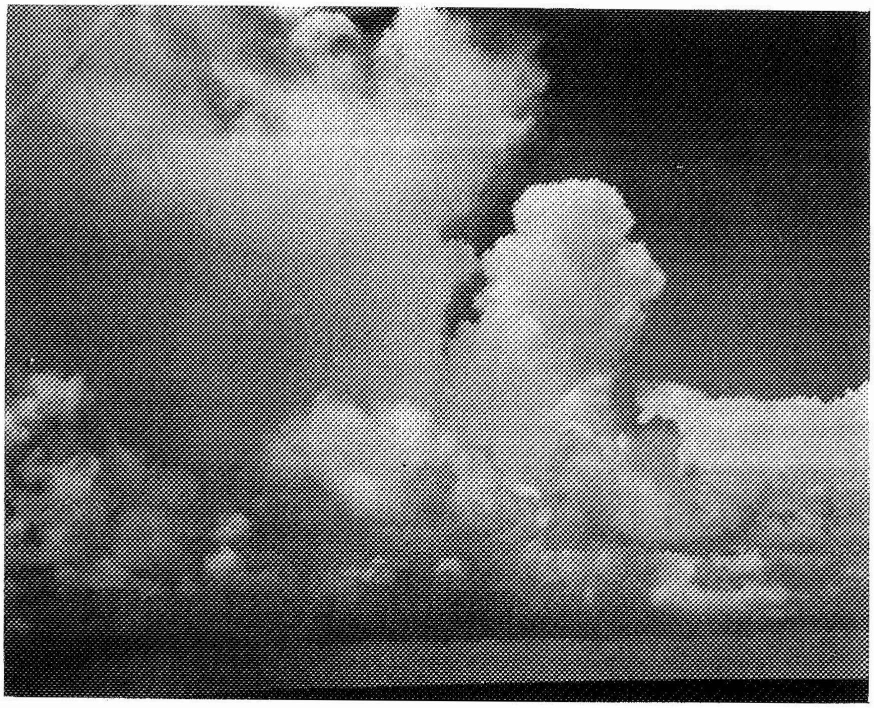


(a) Low cloud tops with cirrus deck overhead. Two funnels protruding from cloud base.

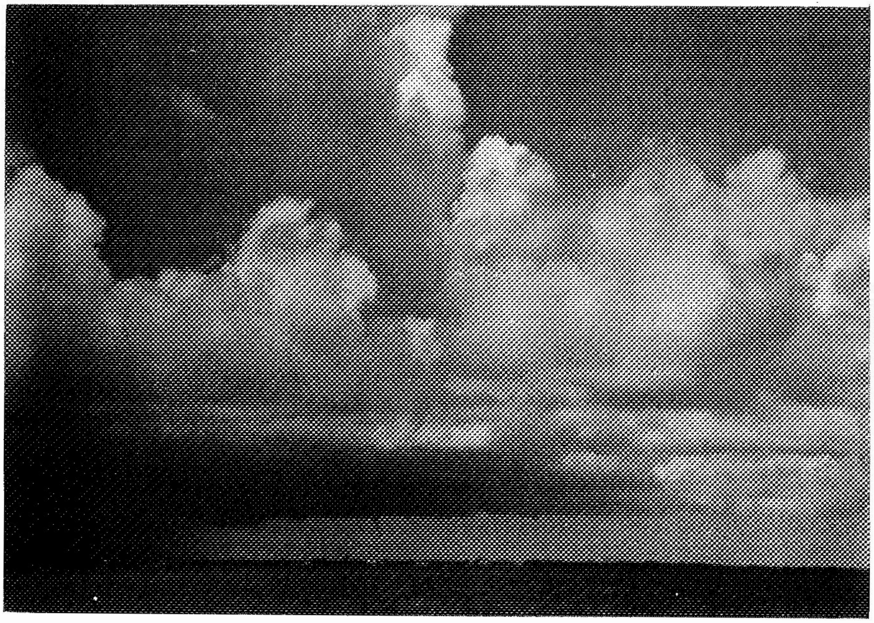


(b) Cloud row with three funnels showing (one merging with rain).

Figure 17.- Eight funnels appeared in sequence from this cloud line, one of which was estimated at over 100 ft in diameter. 0848-0920 EDT, 17 June 1968. Note low altitude of cloud tops and cirrus clouds aloft.



(a) Second funnel forming near east end of cloud row.



(b) Fifth funnel of sequence with rectangular cloud pendant coming down where rain is beginning.

Figure 18.- Six funnels appeared in sequence from low cells at right end of large cloud or row of clouds. Lightning and rain in tall clouds (~25-3000 ft tops) to left of pictures. 1300-1500 EDT, 8 Aug. 1968.

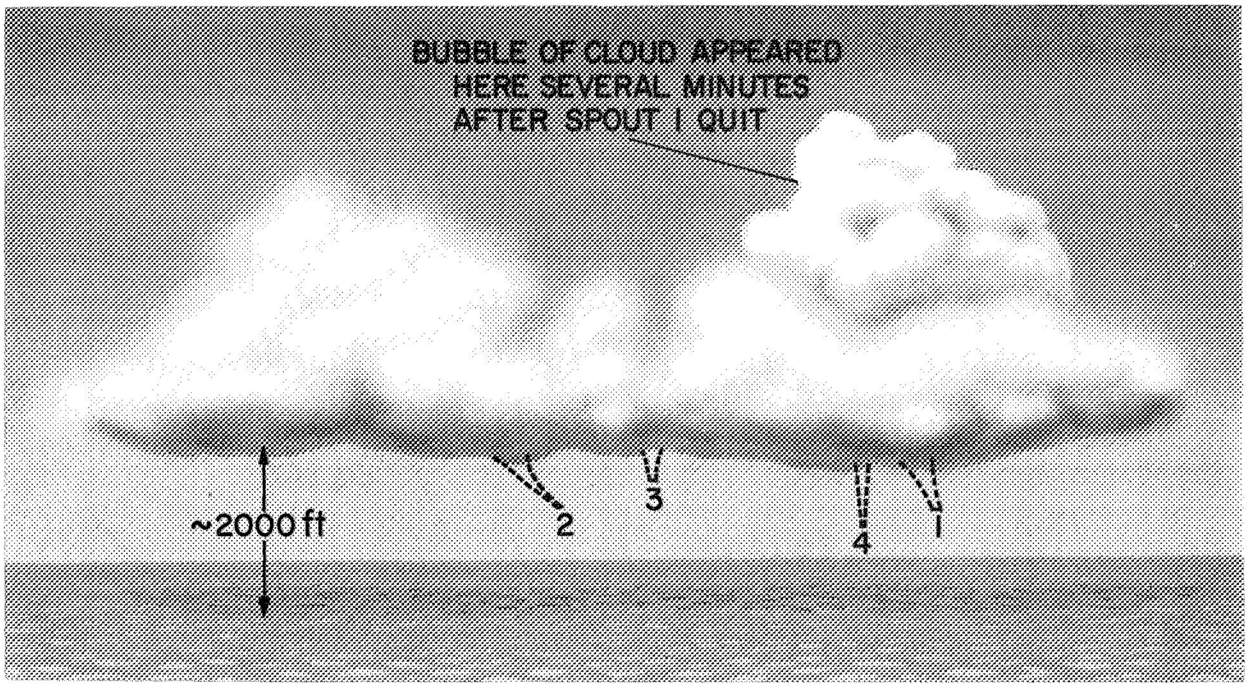


Figure 19.- Sequence of spouts which appeared under clouds of shallow depth and fuzzy tops. Cant and length of funnels varied. Cloud top blossomed out after funnels 1 and 2 expired 1810-1830 EDT, 20 Aug. 1968.

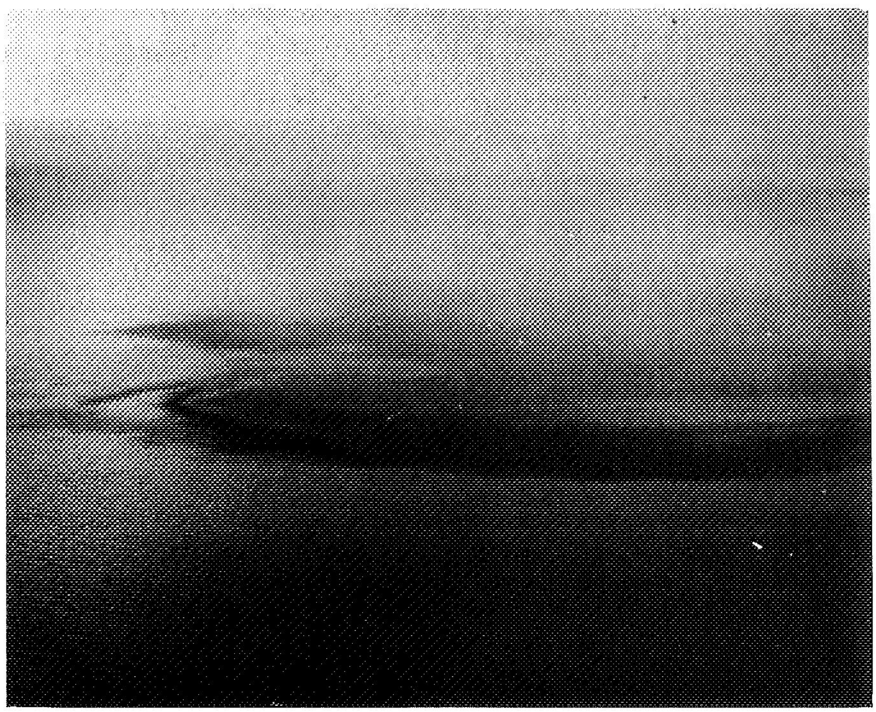


Figure 20.- Example of spiral rain patterns seen on water on occasion. Water devil seen about 5 miles from here. 1400 EDT, 20 Aug. 1968.

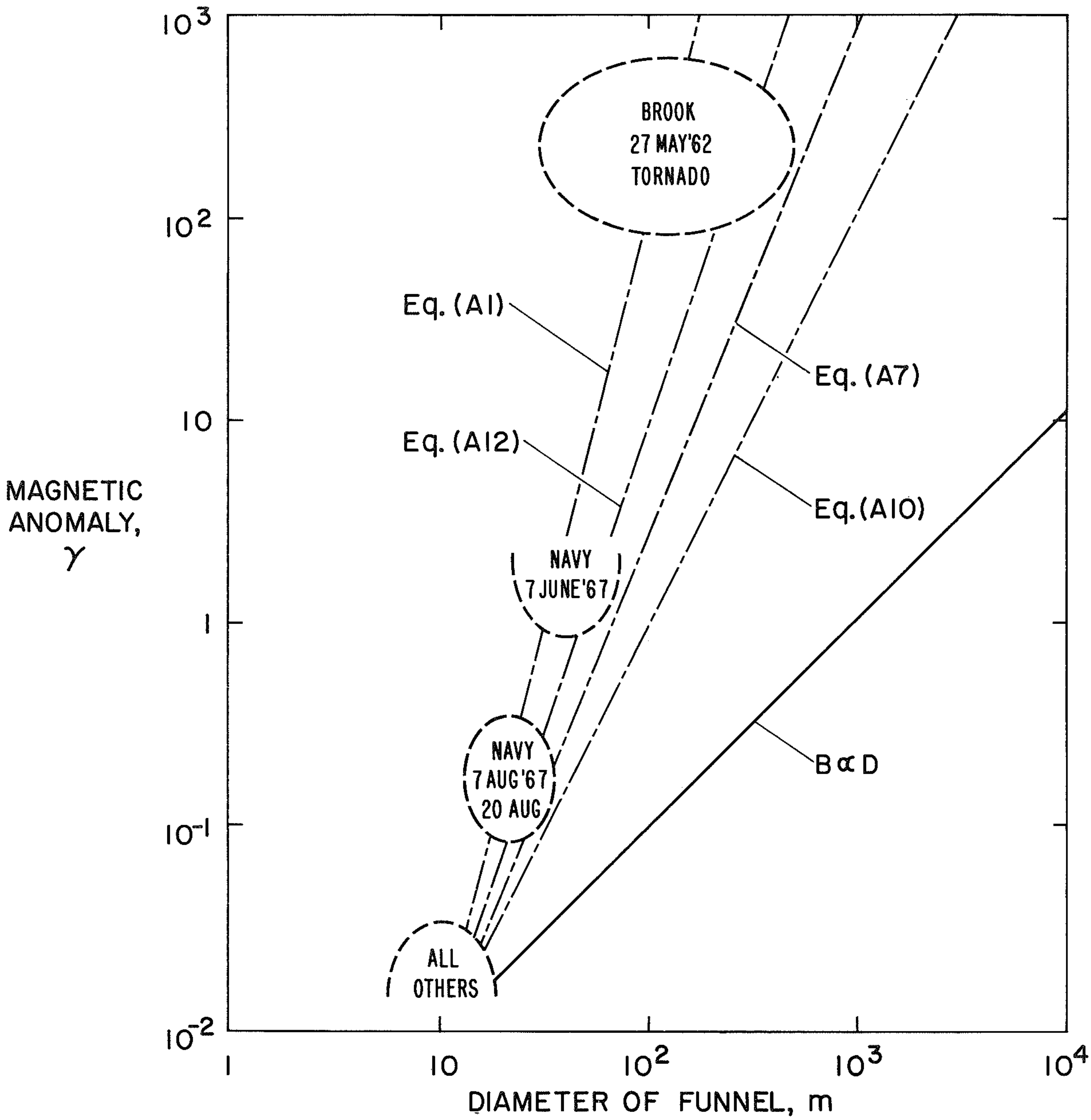
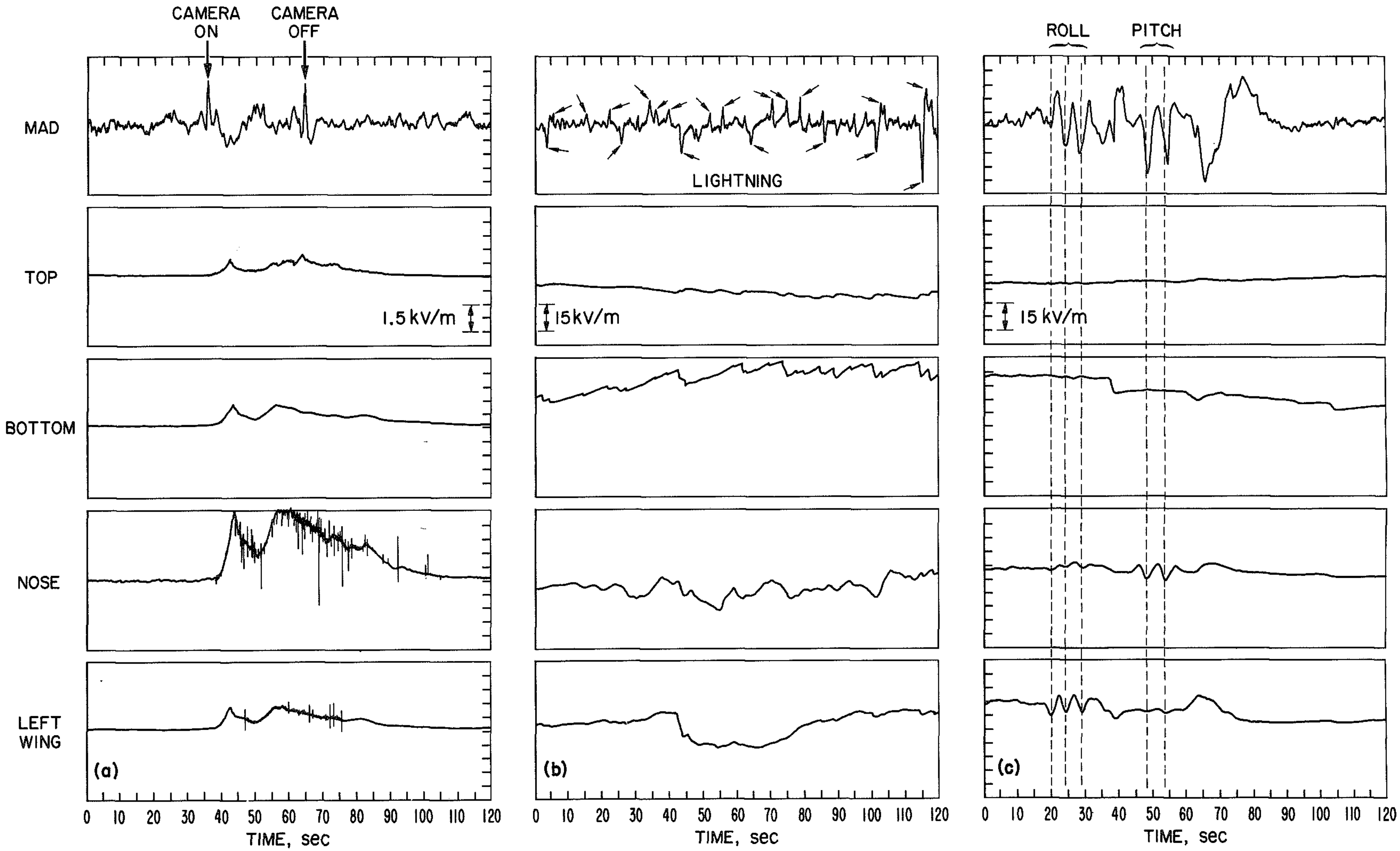
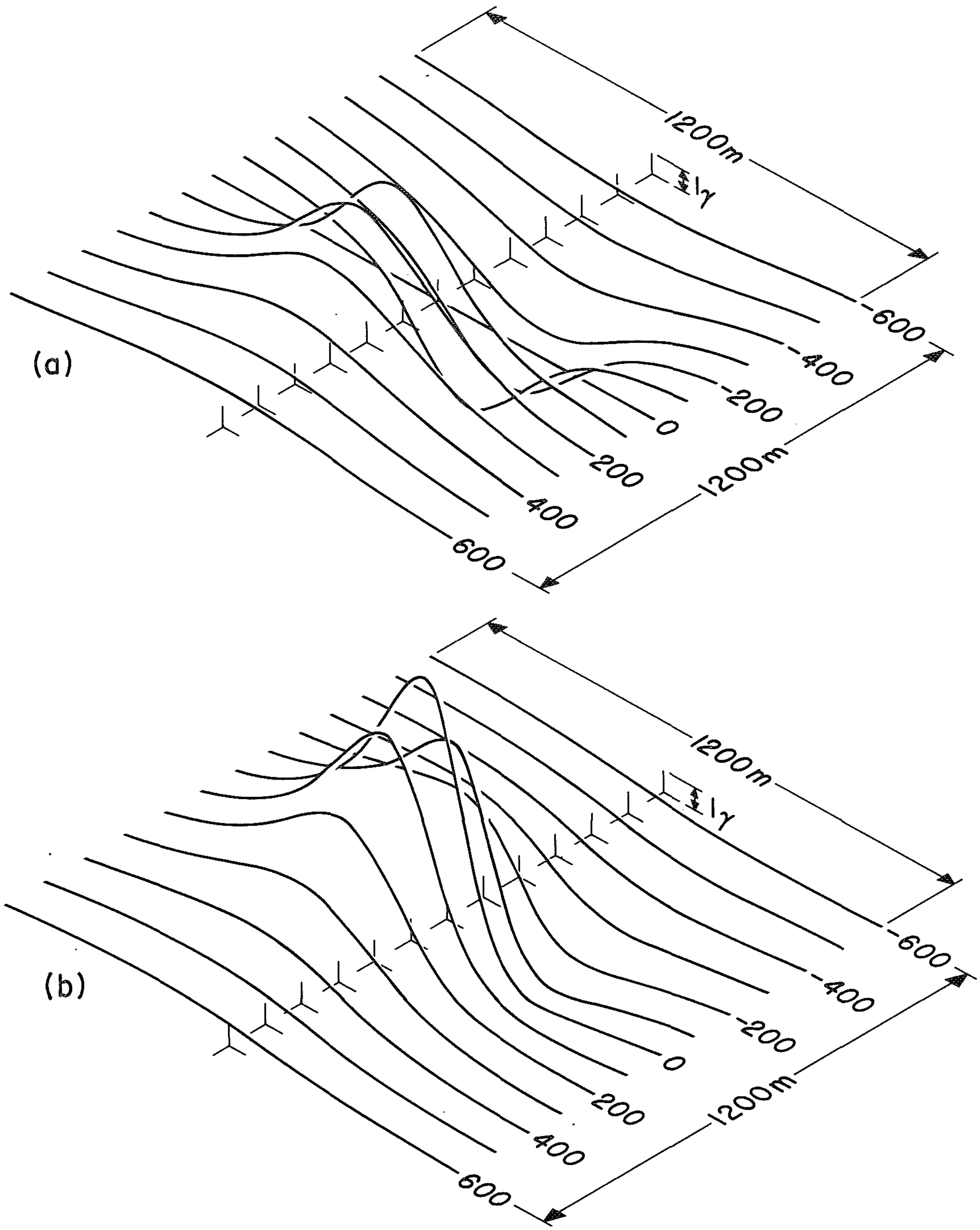


Figure 21.- Theoretical variation of magnetic anomaly with diameter of funnel for various electrical models (appendix A). Enclosures around data points designate uncertainty due to known causes. (Also see footnote 1, page 2.)



(a) Charging of aircraft by a rainshower. 0758 EDT, 2 Aug. 1968.
(b) Signals due to lightning strokes. 1510 EDT, 29 July 1968.
(c) Signals due to pitch or roll of aircraft in an electric field, illustrating crossed-field effects arising because sensors fixed on aircraft. Also note signal in MAD gear by accelerations. 1100 EDT, 2 Aug. 1968.

Figure 22.- Sample signals received on magnetic and electric field sensors.



(a) Current parallel to x axis and 200 m above aircraft flight plane.
(b) Current in xz plane elevated 45° to horizontal with lower end about 130 m above flight plane.

Figure 23.- Profiles of magnetic anomaly calculated in vicinity of electric current line. $I = 10$ A, $l = 200$ m. Earth's magnetic field in yz plane (i.e., y is in magnetic north direction); z axis is vertical.

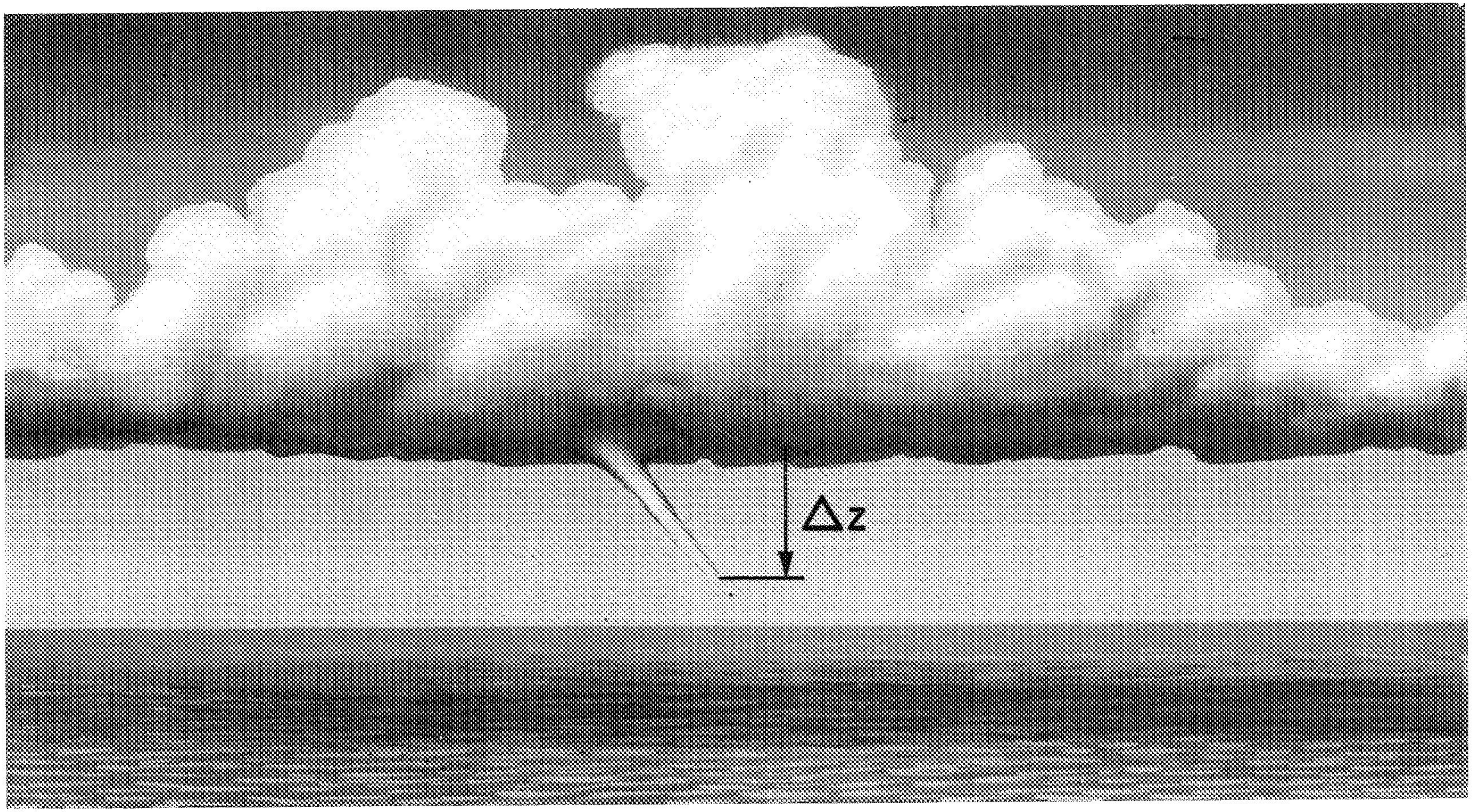


Figure 24.- Sketch of funnel extent below cloud as used in calculation of velocity estimate.

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