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WATER SPOUTS, GUST FRONTS AND ASSOCIATED CLOUD SYSTEMS

Joanne Simpson

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National Aeronautics and
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Goddard Space Flight Center
Greenbelt, Maryland 20771

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WATERSPOUTS, GUST FRONTS AND ASSOCIATED CLOUD SYSTEMS

by

Joanne Simpson

Goddard Laboratory for Atmospheric Sciences

NASA/Goddard Space Flight Center

Greenbelt, MD 20771

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Equation 1 should read

$$\frac{\partial \zeta}{\partial t} = \zeta \text{ conv} - \frac{\partial w}{\partial x} \frac{\partial v_o}{\partial z} \tag{1}$$

p. 11, 2nd line

convergence $\frac{2v_r}{r}$ not $\frac{\partial v_r}{r}$

Equation (4) should read

$$\zeta = \frac{\sqrt{q} \tan \left[\frac{\sqrt{q}\, t}{2} + \tan^{-1} \frac{C}{\sqrt{q}} \right] - C}{2 \tan \Theta} \tag{4}$$

Fig. 1 was calculated with the correct equation.

Abstract

Nine GATE waterspouts have been recorded on five experimental days. From a case study on day 261, we hypothesized (in the Appendix reprint) that necessary ingredients are a rotating cumulus updraft superimposed on much smaller-scale whirl (20-100 m across) in the lower boundary layer. In the day 261 case, we used a three-dimensional cumulus model to investigate cumulus-scale rotation, which is related to wind shear in the lower cloud layer. We postulated that a mechanism to initiate the small low-level whirls could be cold cumulus outflows which would tilt the horizontal vorticity in the lowest 10 m or so into the vertical; subsequent stretching mechanisms were proposed which appeared to produce realistic whirl velocities in 3-5 min.

This report adds another case study on day 186, where two waterspouts were observed associated with a persistent cumulus line whose tops did not exceed 3-4 km. Pictorial evidence was found clearly associating whirl initiation with cumulus outflows. The two waterspouts and the cumulus line were collocated with a substantial, persistent gradient in the sea surface temperatures, which was oriented nearly parallel to the cloud layer wind shear. Primary data were from two superposed aircraft, namely the U.S. Electra (elevation 30-160 m) and the U.K. C130 at cumulus base (about 300 m), which executed three butterfly patterns across the cumulus line, detecting the ocean front radiometrically.

Directly above the ocean front, a strong concentrated sea-breeze like convergence zone was suggested from the winds measured by both aircraft. Estimated convergence magnitude near the waterspouts was

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about 2×10^{-2} s^{-1} in 100 m horizontal distance at the Electra (160 m) level, weakening somewhat toward cloud base. When this magnitude convergence is used to stretch the outflow-tilted vortex tubes, analytical integration of a simplified vorticity equation suggests that a spray ring vortex (tangential velocity above 22 m s^{-1}) could be spun up in 4 min.

This study supports our hypothesis regarding the role of cumulus outflows in waterspout initiation and strengthens Golden's evidence that sea surface temperature gradients may be a key factor enabling modest cumuli to produce waterspouts.

1. Introduction and background

Intensive multi-platform analyses, including photogrammetric cloud mapping on GATE day 261 (see, for example, Warner and Austin, 1978; Warner, Simpson, Martin, Suchman, Mosher, and Reinking, 1979; Warner, Simpson, Van Helvoirt, Martin, Suchman, and Austin, 1980) led to testing a minor modification of Schlesinger's (1978) three-dimensional cumulus model with that data set. Despite realistically weak updrafts (peaks about 6 m s^{-1}), the model clouds exhibited rotation unless the observed vertical wind shear was removed (Simpson, Van Helvoirt, and McCumber, 1982). Vortex pairs with vorticities roughly half that of mid-latitude mesocyclones characterized model clouds in the typical GATE windfield, leading to curiosity regarding waterspouts, together with the recollection that one had been sighted on low-level aircraft film during that day. A preliminary model and observational study of the clouds associated with that waterspout are contained in the Appendix of this report.

The waterspout occurred at the upshear end of a congestus line flanking a typical GATE cumulonimbus (Appendix Fig. 2.3). The cumulonimbus, together with the impacts of its downdraft and gust front system on the subcloud layer, had been modelled in an earlier paper (Simpson and Van Helvoirt, 1980).

The Appendix study concentrates on a model of the waterspout-bearing congestus which was growing in an environment slightly moistened and destabilized by the nearby cumulonimbus. The model congestus showed realistic rise rates, a maximum updraft of 10 m s^{-1} and a cumulus-scale vortex pair with weak vorticities of

80×10^{-4} s^{-1} (Appendix Figs. 4.1 and 4.2). A detailed examination of the terms in the equation for the local time rate of change of the vertical component of vorticity showed that the vortex pair is initiated by tilting the updraft of the horizontal vorticity in the lower cloud layer wind shear and then intensified by stretching, similar to severe storm cases studied, for example, by Klemp and Rotunno (1983). These cumulus-scale vortices are also advected vertically, upward at first and later down to cloud base as downdraft dominates the lower part of the cloud increasingly after 32 min model time (Appendix Fig. 3.2).

A new, rapidly rising tower was observed by a higher level aircraft at the time the funnel was seen extending below cloud base. The cumulonimbus model suggested that the southern portion of its gust front was rain free. The boundary was barely moving southeastward where it probably underlay the waterspout bearing congestus. This was deduced from the model combined with the observed cloud map as follows: the observed distance between the cumulonimbus tower top (Appendix Fig. 5.1) and the waterspout were exactly the same as the model distance between tower top and gust front edge. Thus, model results and observations were consistent with the hypothesis that the funnel was collocated with the gust front convergence zone and density gradient. Golden (1974) noted in his Florida Keys observations that waterspouts frequently were located at the strongest gradient of equivalent potential temperature associated with a cumulus outflow.

In the latter part of the Appendix, it was postulated that the gust front was crucial in the initiation of the funnel studied. It was further suggested that the funnel-scale vorticity (on the order of

10^{-1} s^{-1} or greater) is always available below 10 m elevation. This vorticity is associated with the upward increase of wind velocity in the surface layer, so that its vector is horizontal.

The purpose of this report is to further develop this simplified theory of waterspout initiation and to test it against observations of GATE waterspouts on day 186, where cloud conditions appear strikingly different from those of day 261.

2. Relevant GATE and Florida waterspout observations

a. GATE waterspouts

At the time of the Appendix study, only one other GATE waterspout had been found in the records, namely one of those on day 186 which was spotted by an aircraft pilot and photographed by the aircraft scientist. Some controversy occurred between participants whether the rarity was caused by difficulty of observation or by the necessary coincidence of many cloud and boundary layer processes in critical stages of their life cycles. While day 261 had lower cloud layer stability and somewhat stronger cumulus updrafts than the GATE norm (LeMone and Zipser, 1980), the substantial vertical wind shear associated with the southerly monsoon (Appendix Fig. 2.1) was a daily feature, as were large populations of cumulus outflows and gust fronts which occurred even from relatively small clouds (see, for example, Warner et al., 1980).

By early 1983, a search among GATE participants' films and notes had turned up seven additional waterspouts. Two of the seven were reported on day 261 by an experienced tornado observer. All nine are summarized in Table 1.

It is clear from examining the now available GATE waterspout photographs that, in contrast to the Florida area, the funnels are difficult to identify even by a relatively experienced observer mainly because of poor visibility below cloud base. Furthermore, the GATE funnels were commonly small and short-lived, although three of those in Table 1 produced spray rings. According to Golden (1974), a spray ring indicates tangential wind speeds above 22 m s^{-1}. On day 186, the characteristic early stage dark spots were first rather easily noted on the aircraft film and, after more careful examination, a funnel was

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TABLE 1

Waterspouts recorded in GATE (up to May 1, 1983)

Julian Day	Date	Time	Location	Observer	Remarks
	1974	GMT			
186	5 July	1200	Nr. Quadra	Grossman	No cu above 4 km
186	5 July	1200	Nr. Quadra	Simpson	On aircraft film
252	9 Sept.	0930-1000	SW Quadra	Polavurapu	Spray ring
255	12 Sept.	0930	NW Dallas	Tollerud/Dutton	Spray ring
255	12 Sept.	1110	Nr. Quadra	Polavurapu	Photoed in distance
255	12 Sept.	1930-1940	NW Gillis	Bluestein	Funnel cloud. Moderate towering cumulus
261	18 Sept.	1346	9.75N; 21.09W	Simpson	On aircraft film
261	18 Sept.	1835	W. Gillis	Bluestein	Funnel cloud
261	18 Sept.	1845	N. Gillis	Bluestein	Two funnels. One became waterspout with spray ring

TABLE 2

Order of Magnitude of Variables

Associated with GATE Gust Fronts

At ∼10 m Elevation

(One Minute Averages)

Variable	Symbol	Magnitude	Remarks
Vertical Vorticity	ζ	$\pm 10^{-2} s^{-1}$	Peak Value
Convergence	Conv.	$10^{-2} s^{-1}$	
Updraft Gradient	$\partial w/\partial x$	$2 \times 10^{-3} s^{-1}$	Near Gust Front
Updraft Max	w_{max}	0.2 m/sec	Near Gust Front
Draft Radius	Δx	100 m	Could be Less
Ambient Windshear	$\frac{\partial V_0}{\partial z}$	$10^{-1} s^{-1}$	Logarithmic Profile
Tilting Term	$\frac{\partial w}{\partial x} \frac{\partial V_0}{\partial z}$	$0.2 \times 10^{-3} s^{-2}$	Conservative

detected protruding downward from the cloud. Enough waterspouts have been found at this time to feel reasonably certain that more would turn up if all the film, from both low-level aircraft and the ships, were painstakingly examined. In particular, Table 1 shows multiple waterspouts on all days which have so far been intensively studied. At present, this excludes September 9 on which no aircraft flights were made in the GATE ship array.

b. Variables associated with GATE gust fronts

Extensive observational analyses of GATE gust fronts were carried out by Garstang[1] and colleagues at the University of Virginia. Some of the material appears in a dissertation by Addis (1983). Particularly relevant to this study are observations made by the instrumentation on the ship's boom at 10 m and on the tethered sounders. It was noted that vertical velocities on the scale 20-100 m were greatly enhanced just ahead of gust fronts. Since the tilting term ahead of a gust front and the convergence and vorticity associated with the density boundary are of particular interest to the hypothesis in this report, typical values are shown in Table 2. These values are 1 minute averages (corresponding to a horizontal distance of about 300 m); shorter-interval values can be considerably higher.

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[1]Many of the analyses appear in a report to the National Science Foundation entitled "The Tropical Atmospheric Boundary Layer, Part II" by M. Garstang, J. Simpson, G. D. Emmitt, E. Augstein, G. M. Barnes, D. Fitzjarrald, R. Addis, E. Tollerud, and C. Warner. Department of Environmental Sciences, University of Virginia, Charlottesville, VA, September, 1980, 105 pp. Additional information on the short-term variability of parameters at elevations of 10 m near and across GATE gust fronts has been obtained in personal communications from R. Addis and G. D. Emmitt.

The z axis points vertically upward; $\mathbf{V}_0$ is the prevailing horizontal wind velocity vector, so that $\partial\mathbf{V}/\partial z$ is the ambient low-level shear. On day 261, $\mathbf{V}_0$ is from the south, the x axis points to the east, normal to the density boundary (Appendix Fig. 5.2) directed from denser to less dense air.

c. Florida waterspout observations

Florida waterspouts have measured circulation velocities of 4-35 m s^{-1} with diameters ranging from 7-150 m. Funnel velocities are 10 m s^{-1} or greater (Golden, 1974). Schwiesow (1981) added to Golden's information using airborne Doppler lidar to obtain the three-dimensional velocity fields in and near the waterspout funnels. Results showed rough coincidence between the funnel wall and the outer limit of the solid rotation, characterizing the inner vortex, which will be used in the theoretical development to follow.

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3. Hypotheses for funnel-scale vortex initiation in the lower planetary boundary layer (PBL) and for the connection to overlying cumuli

a. Physical postulates

It is hypothesized firstly that a gust front boundary may tilt prevailing horizontal vorticity into the vertical at low levels (on a horizontal scale of 10-100 m) and that the vorticity is then further intensified and concentrated by the convergence associated with the gust front. Pre-existing vertical vorticity in the gust front zone may also contribute to the rapid spin-up of a funnel-sized whirl or several whirls (cyclonic or anticyclonic) along a line or arc. These whirls may make themselves visible under low wind conditions as roundish dark spots on the water surface.

Secondly, to develop a full waterspout, a cumulus with rotation as described in the Appendix model study, with a new actively rising tower, must pass somewhere nearly above the low-level whirl. Emmitt (1978) has shown that even fairly modest GATE cumuli had "roots" or cumulus-scale updrafts extending continuously down into the upper PBL as detected by the ship's boom instrumentation at 10 m, as well as by the wire-mounted sounders. These cloud roots may be envisaged as a population of "tentacles" reaching down into the interface layer which may "catch" a low-level vortex from time to time. A similar process is apparently seen on the film of the Purdue laboratory experiments (Snow, 1982) when a surface whirl suddenly is connected up into the larger scale rotating ascent created by the warming and the fan.

Actually, in the day 261 case studied, the superposition of the vortex containing cumulus congestus with its new tower roughly above

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several surface whirls may not be entirely coincidental, as the cumulonimbus outflow may provide the forcing function for the new cumulus tower as well as the tilting of the lower boundary vorticity. The cumulus tops in the postulated vicinity of the outflow boundary had a "boiling" appearance on the aircraft film, which was quite different from those tops away from the vicinity of the cumulonimbus.

4. Simplified analytical approach to funnel-scale whirl initiation

The local time rate of change of the whirl's vertical velocity ζ will be assumed to be determined by tilting and stretching only, namely

$$\frac{\partial \zeta}{\partial t} = \text{conv} - \frac{\partial w}{\partial x}\frac{\partial V_o}{\partial z} \tag{1}$$

where most of the symbols were explained in connection with Table 2. All other terms in the vorticity equation can be shown to be much smaller than these two on the space and time scales considered, namely 10-100 m, 1-5 minutes. The vortex will be assumed to be in solid rotation so that $\zeta = 2\omega$ where ω is the angular velocity. Therefore,

$$V_\Theta = \frac{\zeta}{2} r \tag{2}$$

where V_Θ is the tangential velocity and r is the radial distance from the center. The tangential velocity is maximum at the funnel wall r_W, assumed 25 m here (Appendix Fig. 2.4).

The tilting term will be held constant at the value shown in Table 2. Actually, w might increase during vortex development and V may also be altered, but only early stages are under consideration.

Equation (1) will be solved for three cases, as shown in Table 3.

Physically, in Case 1, the gust front convergence (assumed constant) aids the tilting provided by the eddies just ahead of it, but no initial vertical vorticity is assumed. Case 2 is identical except that the gust front is assumed to have the initial vorticity given in Table 2. In Case 3, early connection between the whirl and the cloud roots has begun, causing spiralling inflow at a 10° angle, consistent with the photographs of Golden (1974). In this case, a radial velocity,

$v_r = V_\Theta \tan \Theta$, occurs at the funnel edge, vanishing at its center so that a convergence $\frac{\partial v_r}{r}$ is added to the value in Table 2.

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TABLE 3

Vortex Initiation Cases

	Tilting	Conv	ζ_o	Inflow Angle Θ
Case 1	As Table 2	As Table 2	0	0
Case 2	As Table 2	As Table 2	As Table 2	0
Case 3	As Table 2	Increasing from Table 2	0	10°

The analytic solution to equation (1) in Cases 1 and 2 is

$$\zeta = \frac{L}{C} (e^{Ct} - 1) + \zeta_o e^{Ct} \tag{3}$$

where L denotes the tilting term and C denotes the convergence term, both constant by assumption.

The two right-hand curves (x-dashed and solid) in Fig. 1 show the development of vertical vorticity and maximum tangential velocity (from equation 2) for these two cases. Reasonable whirls with speeds of 5 and 7.5 m s^{-1}, respectively, exist after 5 minutes.

When 10° inflow is superimposed in Case 3, so that convergence increases with time, the solution becomes

$$\zeta = \frac{\sqrt{q} \tan\left[\frac{\sqrt{q}t}{2} + \tan^{-1} \frac{C}{\sqrt{q}} \right]}{2 \tan \Theta} \tag{4}$$

where $q = 4L\tan \Theta - C^2$

The triangled (dashed) curve in Fig. 1 shows that the vorticity and tangential velocity go to infinity by 3 minutes in this situation, meaning that other forces such as friction become important, or conditions change substantially, or both. The significance of the result is the enormously enhanced growth rate of the vortex caused by the imposition of intensifying convergent inflow, postulated here to be

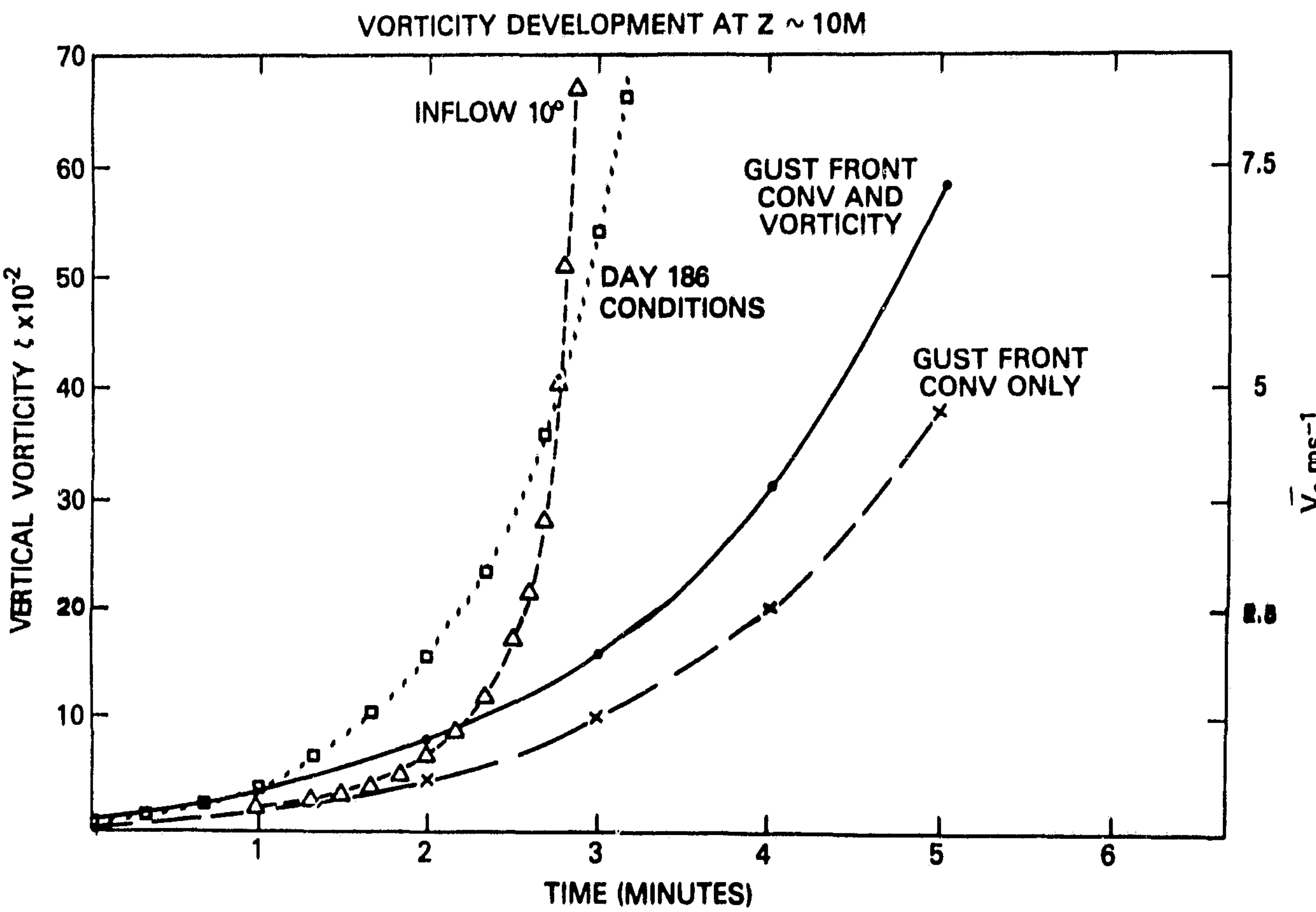

Fig. 1. Vorticity and Tangential Velocity Development with Time in Early Stage of Low-level Funnel-scale Whirl. The calculations for vorticity are made from equation (1) and for V_θ from equation (2). Initial conditions for 3 curves (x-dashed; solid, with circles; dashed with triangles) found in Table 3. Curve labelled "Day 186 conditions" (dashed, with squares) is discussed in Section 5d.

a consequence of the rotating ascent above the surface whirl. In this example, the vortex would create a spray ring at 175 secs.

The cornerstone of the present hypothesis is the role of the cumulus outflow boundary in initiation of one or more low-level whirls which are in earliest stages vertically separate from a rotating cloud updraft above, which may or may not be placed there by interaction with other cumuli.

To test that part of the hypothesis regarding initially unconnected (in the vertical) whirls on different scales will be difficult observationally. To find other evidence from GATE data that cumulus outflows play a role in the small vortex initiation process will next be attempted.

5. Observational analyses of waterspouts on GATE day 186

a. Overall conditions and distinguishing features

GATE day 186 was selected from the Table 1 cases primarily because a waterspout and its associated clouds were observed from the U.S. Electra aircraft. That aircraft was flying repeated butterfly patterns as the lowest member of a four aircraft vertical stack; this meant that some spatial and temporal data coverage was likely, in probable contrast to the cases involving ship sightings which may be studied later. Other reasons for selection of day 186 were 1) the cumulus development was suppressed in considerable contrast to day 261 and 2) highly experienced observers were involved in the aircraft flights[2].

On day 186, a line of small cumulus, some few of which were showering, persisted in the vicinity of the ship QUADRA through at least daylight hours. At no time did the tallest towers exceed 4 km. This figure was estimated by the aircraft scientists at the time and checked by using the Electra film during this study. Figs. 2 and 3 show that the line was oriented from about southwest to northeast (actually 215° to 035°). The clouds of interest were located about 120 km almost due north of the QUADRA.

The prevailing wind shear around waterspout time (near 1200 GMT) was difficult to determine since the ship winds failed and back-up dropwindsondes were finished several hours earlier. It was estimated

[2]Dr. Edward Zipser was Airborne Mission Scientist and Dr. Robert Grossman was the Electra Scientist who noticed and photographed the waterspout. Both have been enormously helpful in the analysis.

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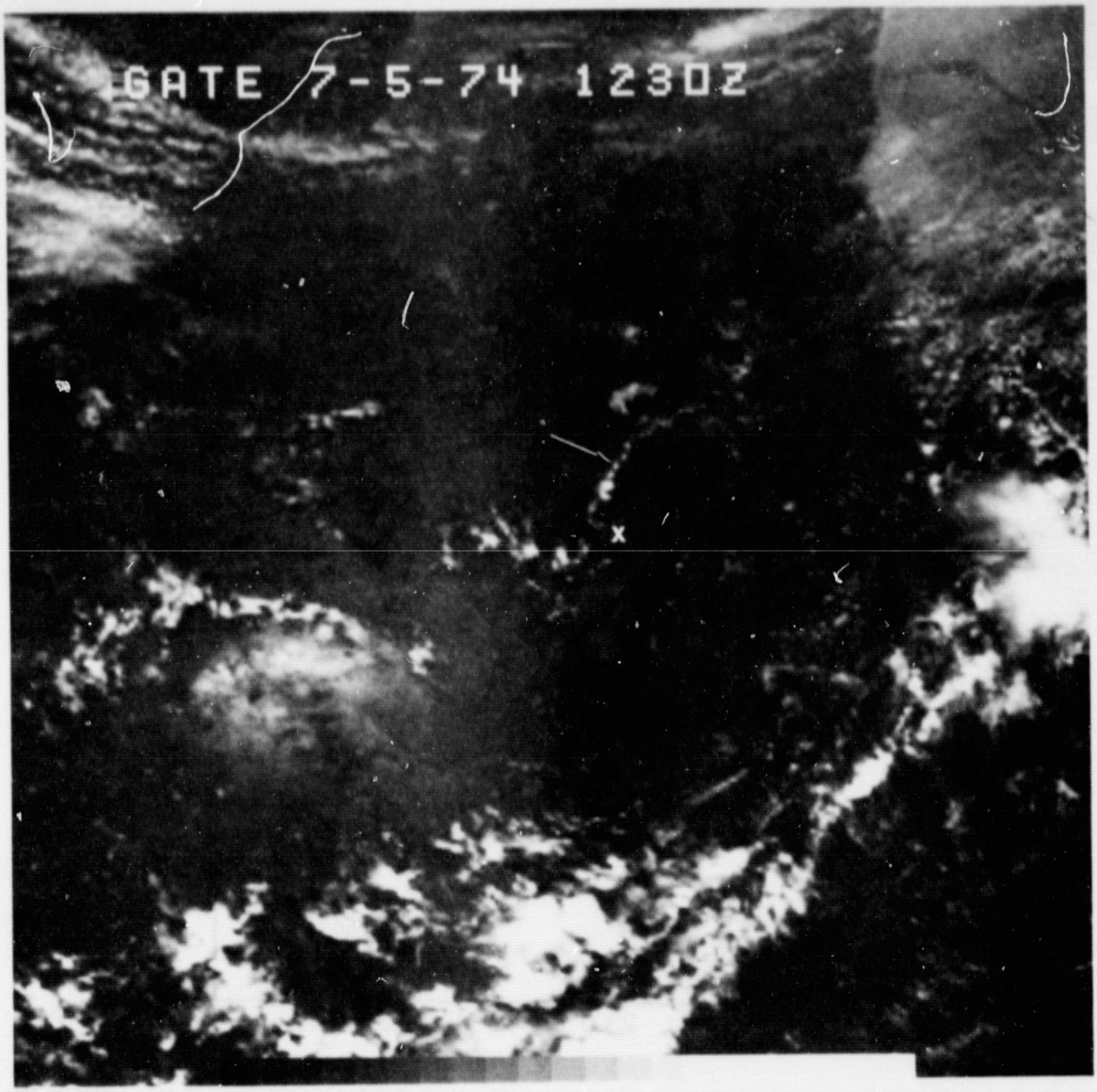

Fig. 2. GOES Visible Image at 1230 GMT on GATE Day 186 (July 5, 1974). Arrow points to waterspout location. Ship QUADRA position indicated by x.

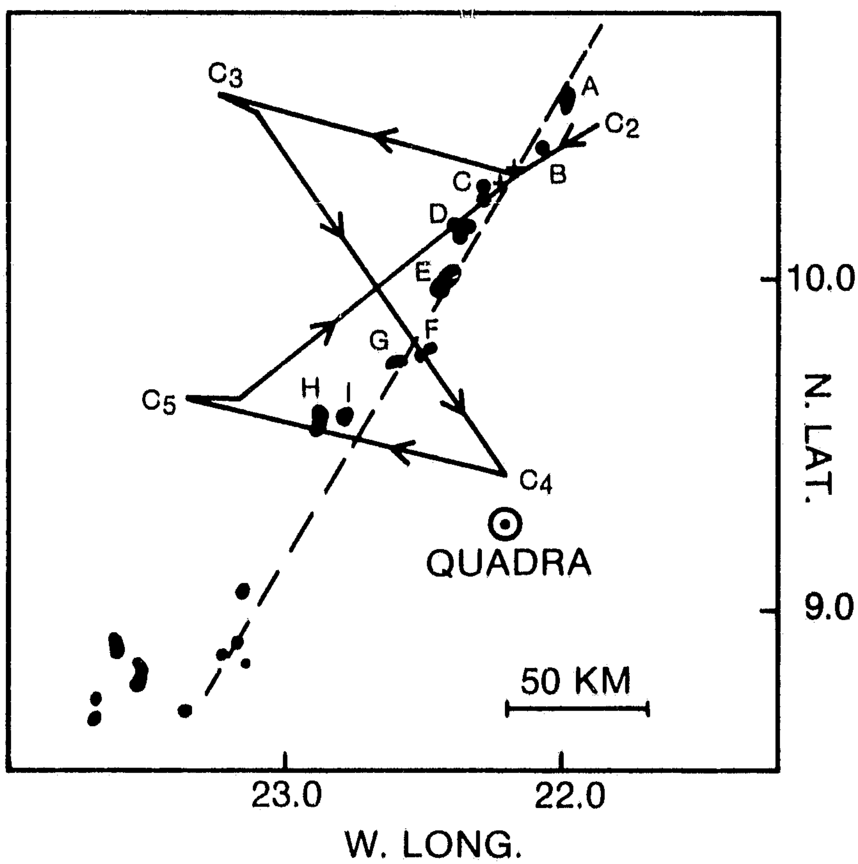

Fig. 3. PPI Radar Echoes from Ship QUADRA for 1157 GMT. The dashed line, constructed by eye, indicates the NNE-WSW orientation of the echo line. The first of the three butterfly patterns executed by the Electra aircraft has been superposed to scale. The other three aircraft executed the same pattern at higher levels. The two waterspouts, found on the Electra film between 1200-1201 GMT one on each side of the aircraft track are denoted by X's. Note that the waterspouts were found between and not far from echoes B and C.

from flight-level winds on board the several aircraft, together with cloud pictures obtained from the Electra, that the shear in the lower two-thirds of the cloud layer was closely parallel to the cloud line, from roughly southwest, with a magnitude between 2.5 to 4 m s^{-1} km^{-1} depending how one treats the reported flight-level winds from the French DC-7 aircraft. In any case, the magnitude was comparable to that on day 261, although the direction was almost opposite.

The thermodynamic conditions of the atmosphere are shown in Fig. 4. The Electra sounding locations are indicated on Fig. 5. Despite the substantial distance from the QUADRA, the ship and aircraft soundings made at the same time are quite similar to each other. The much more suppressed convection on this day relative to day 261 is illustrated by a drier sounding on day 186, together with a pronounced stable layer based at 850 mb. Around noon only the tallest clouds attained heights above the stable layer. As the afternoon progressed, the stable layer became stronger (Fig. 4b), associated with further suppression of convection. No tops above 2.4 km were measured by 1530 GMT. By 1500 GMT, very few showers were occurring along the cloud line, while near the location of the earlier waterspouts small cumuli were still actively growing although none produced precipitation.

The two waterspouts were recorded on the film nearly simultaneously (1200-1201 GMT). Locations are noted on the schematic cloud map (Fig. 5). It was difficult to determine the height of the cumulus tops overlying the waterspouts from the Electra film. The highest tops in their vicinity appeared to be roughly 4 km from the aircraft's turning descent five minutes earlier, in agreement with the aircraft scientist's

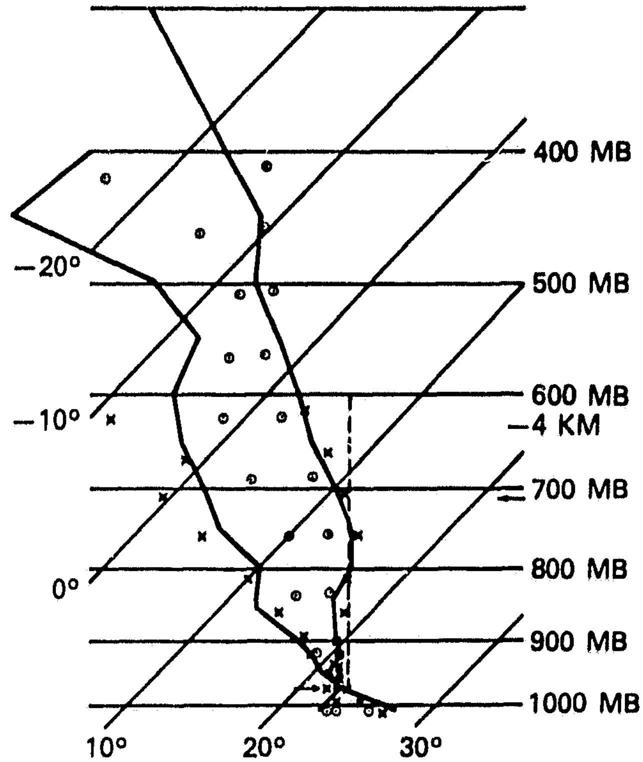

Fig. 4a. GATE Day 186 Soundings for 12 GMT. The Electra values obtained on descent into the butterfly pattern between 1145 and 1200 GMT as indicated on Fig. 5. Lower arrow denotes observed cloud base, 4 km indicates estimated tops of tallest clouds.

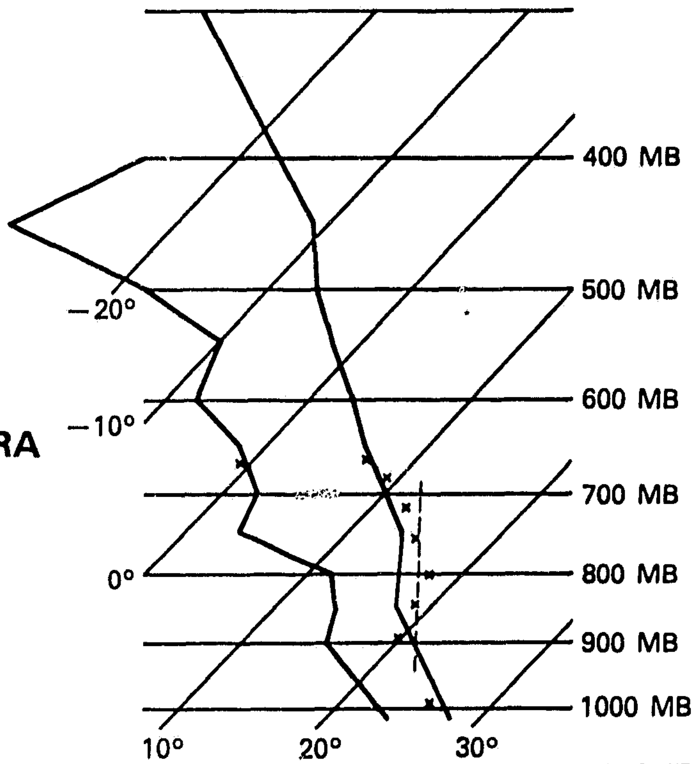

Fig. 4b. GATE Day 186 Soundings for 1600 and 1800 GMT. QUADRA sounding was made at 1800 GMT. Electra sounding was made on ascent out of the butterfly pattern (see Fig. 5) at 1600-1610 GMT. Note pronounced stabilization and drying relative to earlier soundings in Fig. 4a.

Fig. 4. GATE thermodynamic soundings of temperature and dewpoint plotted on tephigrams. The dashed line is the wet adiabatic ascent from the observed cloud base. The solid lines are QUADRA soundings, X's are obtained by the U.S. Electra aircraft and the circled dots comprise the sounding used in the Appendix for the day 261 model cloud which produced a waterspout.

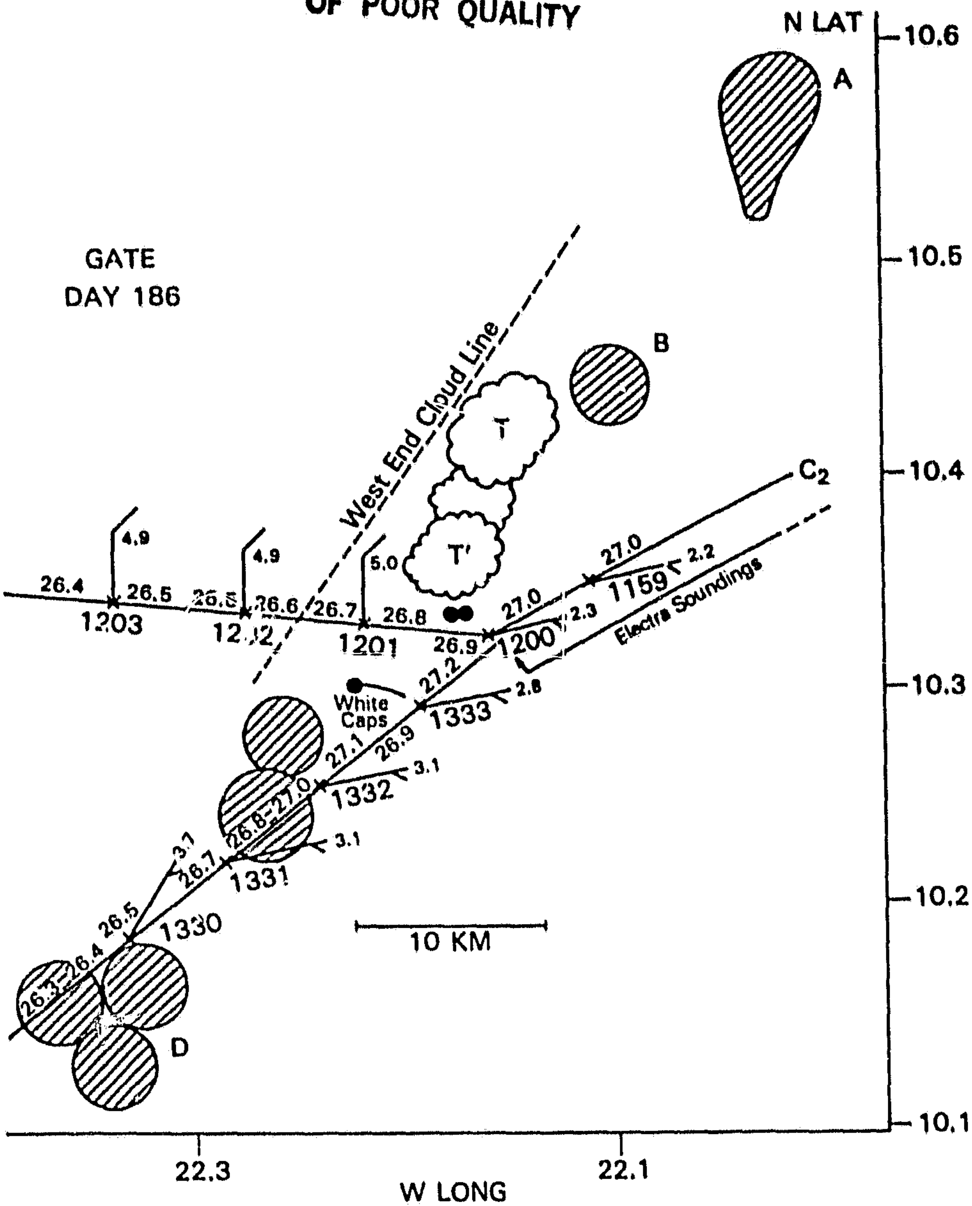

Fig. 5. Schematic Map of Significant Features. Note waterspout-associated dark spots, QUADRA-observed radar echoes. Electra aircraft track (times are the four digit numbers (from 1159-1203 GMT and from ~1330-1333 GMT), corrected sea surface temperatures (SST's) as obtained from the Electra radiometer (three digit numbers), one-minute average flight-level winds with speeds indicated in m s $^{-1}$ (two digit numbers). Wind barbs are plotted conventionally in knots, with one-half barb for each five knots. Only two of the tallest cumulus towers seen on the film are plotted, namely T and T' which were estimated close to 4 km. Similar appearing towers were located approximately above showers C and D but could not be measured. Both waterspouts were beneath non-showering clouds which extended across the aircraft track and on to the west-southwest. There were several parallel lines of non-showering cumuli to the east (warm ocean) side of the shower line and virtually no cumuli, except occasional extremely suppressed fractocumuli to the left of the dashed line labelled "West End of Cloud Line." The Electra soundings were made on descent (1145-1200 GMT) and ascent (1600-1610 GMT) into and out of the pattern terminating and beginning, respectively, at the left end (arrow) of the line indicated. The dark spots are drawn larger than to scale to be made visible. The dark line (inferred to be gust front edge) connected to southern dark spot is drawn roughly to scale.

recorded estimate. No cloud top which could be measured later by careful photogrammetry exceeded about 3.2 km. Fig. 4 suggests that cumuli would have to be strongly dynamically forced and/or the sounding altered in their vicinity to attain top heights of 3-4 km around noon (Fig. 4a) and 2.4 km around midafternoon (Fig. 4b).

The actual funnels are hard to see on the photographs (Fig. 6) but the circular dark spots on the water are clearly visible. There were two distinct dark spots associated with the northern waterspout (the one photographed by aircraft scientist Grossman) and possibly more with the southern more distant waterspout which was detected during our film analysis. The funnels measured 25-30 m across; the dark spots had diameters of about 150-200 m. According to Golden (1974, loc. cit.), the dark spots appear at the earliest detectable stage of waterspout development. A dark spot may or may not become associated with a downward developing funnel.

The most important feature relevant to the theory is noted on Fig. 6 where the dark spot related to the southern funnel appears at the end of a dark line on the water, to the south of which occasional whitecaps could be seen; these were also noted by the aircraft observer on the UK-C130 aircraft. In both waterspout cases, a shower can be seen further away from the aircraft in the background. The evidence is therefore, substantial that these waterspouts were collocated with outflow boundaries from showering cumuli.

b. The maintenance of the cloud line by the ocean temperature gradients

The persistence of the cloud line for more than 9 hours in the same position together with the strange appearance of the sea surface noted

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Fig. 6a. Print from right side-looking 16 mm movie film showing north waterspout funnel (black arrow) just beginning and two sea surface dark spots (white arrows). Time 1200 GMT plus about 3 sec. Camera aimed toward 12° East of North.

Fig. 6b. Print from hand held 35 mm camera (slide) by aircraft scientist Dr. Robert Grossman. Camera aimed toward northeast. Arrow notation same as a. Time 1200 GMT plus about 9 sec.

Fig. 6. <u>Photographs from Electra Aircraft on GATE Day 186.</u>

Fig. 6c. Print from left side-looking 16 mm movie film showing south waterspout funnel (black arrows), surface darkspot (short white arrows) and edge of gust front (larger white arrows). Time 1201 GMT; camera aimed toward 12° West of South.

Fig. 6d. Print from left side-looking camera at 1446 GMT (second butterfly), camera aimed toward northeast, showing that cloud layer shear is from about southwest. This cloud's top is at about 3.2 km, typical of the increasing suppression with time.

Fig. 6. Photographs from Electra Aircraft on GATE Day 186.

on the film and by all aircraft observers suggested that ocean structure may have been responsible for its sustenance. The western portions of the butterfly patterns had virtually clear skies, weak surface winds and strange smooth streaks, wavy patterns and blobs on the sea surface reminiscent of the upwelling eddy patterns often noted in strong tidal currents and at the edge of the Gulf Stream.

The sea surface temperatures (SST's) as measured by PRT-5 radiometers on the Electra and UK-C130 aircraft were carefully examined, before and after correction for the effects of water vapor below the aircraft. On both aircraft records, an SST gradient of 0.5-1.0°C was found concentrated in a band less than 20 km wide extending apparently continuously for more than 170 km in a northeast-southwest direction. The real gradient across the band was probably stronger since the water vapor intervening between aircraft and surface reduces gradients as well as absolute values of remotely detected SST's (Brown and Evans, 1982). The Electra was at 160 m elevation when passing the waterspouts (it flew at 30-90 m later) and the C130 was at 300 m, just below cloud base. The graphically estimated corrections were 0.3C and 0.5C, respectively. The SST's plotted on Fig. 5 are the Electra corrected values. The C130 corrected values give an absolute value of SST about 0.5C higher, although gradients corresponded almost perfectly. The higher values are more consistent with the soundings in Fig. 4a and the cloud structure.

The cloud line was located over the region of strongest SST gradient, not over the warmest water. If we use the C130 SST's, the sea surface temperature was 0.4-0.5C warmer than the lowest air on the east side of the cloud line, with the sea-air temperature difference decreasing to zero or slightly negative as the suppressed region west of the cloud line was reached[3]. The surface air temperature in Fig. 4a was estimated from the lowest point on the Electra sounding at 100 m by using a dry adiabatic lapse rate down to the sea level pressure as determined at the QUADRA.

It is not known for certain that the approximate alignment of the sea surface isotherms with the wind shear vector in the cloud layer was fortuituous. In any case, the coincidence should have strengthened the cloud line, since orientation along the shear vector is generally favored (Malkus and Riehl, 1964). However, the primary forcing of the cloud line and the reason for its being anchored on the SST gradient is hypothesized to be wind convergence related to a sea-breeze type circulation produced by the horizontal temperature gradient. Malkus (1957) showed that SST gradients of this magnitude or less are often associated with cumulus groups in the western tropical Atlantic; she estimated the magnitude of the "seabreeze" circulation using "equivalent mountain" theory.

To pursue this idea the low level windfield is examined next.

c. The low-level windfield

The Electra aircraft data were obtained in the form of both 1-minute and 1-second averages. Winds were plotted for all three butterfly patterns (the last incomplete) and examined for side-slip bias, which appeared to be negligible. A substantial wind shift occurred every time the aircraft crossed the cloud line. Winds were from easterly on the east side shifting to northerly on the west side.

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[3]Both SST's and low-level air temperatures increased slightly toward the south, the data suggest 0.5-1.0C increase from C_2 southward to the QUADRA.

The shear vorticity was cyclonic with convergence obvious; the wind shift occurred exactly at the waterspout location as seen in Fig. 5.

The amazing finding occurred when the 1-second winds were examined. The windshift took place virtually entirely between consecutive 1-second values, namely it was confined to an interval of about 100 m in the horizontal! An attempt was made to estimate both rectangular components of the convergence and the vorticity. This procedure can have pitfalls but the results regarded on a "what if" basis are thought-provoking.

The convergence and vorticity (at 160 m elevation) jumped to 1-second peaks of $2\times10^{-2}s^{-1}$ and $7\times10^{-3}s^{-1}$ respectively, nearest to the waterspout location! When the aircraft repeats the same path 1 hour and 38 minutes later, the estimated convergence is still about the same, although the cloud tops are lower, waterspouts are not observed and showers are no longer seen on the film. If these estimates are even approximately valid, the implication is that the forcing by sea temperature gradient and low-level air convergence remained fairly constant while the convective response of the atmosphere weakened because of the stabilization and drying (Fig. 4b).

The most important finding, however, is the concentration of convergence on the PBL eddy scale - essentially the funnel scale - and what this concentration may mean for vortex development. The concentration of the convergence, regardless of the question regarding magnitude, is almost surely outside the errors of the aircraft instrumentation, particularly since it was encountered each time the aircraft crossed the cloudline and at no other places in the flight pattern.

Supporting evidence was found in the 1-second data from the UK C130. At 300 m, the windshift located above the warm edge of the SST gradient was in the same sense but much less pronounced than that observed by the lower aircraft, owing in considerable part to the stronger winds at cloud base (about 4 m s^{-1} versus 1-2 m s^{-1} at the lower level) in the crucial region near the waterspout location. However, the estimated convergence in the 100 m horizontal interval of the windshift was roughly half as great at cloud base as that estimated from the Electra winds at 160 m. This upward decrease of convergence is consistent with theories and observations of tropical seabreezes (Malkus, 1957) and less consistent with an alternative hypothesis that the clouds themselves caused the convergence below them.

d. Vortex growth hypothesis considered with day 186 evidence

On day 186, there may have been one more ingredient present to spin up a funnel-scale vortex than those we hypothesized for day 261. As postulated for day 261, there were cool outflows from showering clouds, whose boundaries evidently were collocated with the dark spots on the water. The postulate regarding tilting could equally well apply - and is equally untestable with the existing data. However, on day 186, the waterspouts formed in a concentrated convergence band whose magnitude may have been as great as $2\text{x}10^{-2}s^{-1}$ on the 100 m scale.

Hence, we will apply equation (3) under the following conditions:

Tilting term	=	$0.2\text{x}10^{-3}s^{-2}$ (constant)
Convergence	=	$2\text{x}10^{-2}s^{-1}$ (constant) from obs
Initial vorticity (ζ_o)	=	$5\text{x}10^{-3}s^{-1}$ from obs.

The dashed-dotted curve in Fig. 1 gives the result. The vortex growth rate is more than tripled by the superimposition of the doubled convergence; this model vortex would spin at $V_\Theta = 22.7\ m\ s^{-1}$ at 4 min, thereby casting up a spray ring.

6. Conclusions, questions raised and recommendations

The evidence from GATE day 186 appears strongly supportive of a key portion of the hypothesis advanced in the Appendix regarding waterspout initiation. It is not inconsistent with the remainder. Day 186 data, particularly Fig. 6, shows a waterspout located at an outflow boundary, in support of the postulate that convective outflows can play a crucial role in their generation.

Different originating mechanisms appeared to provide the key ingredients on the two days. On day 261, the hypothesis was that the tilting by and convergence in the gust front outflow from a nearby cumulonimbus initiated the low-level funnel scale whirl. On day 186, which was much more suppressed, it appeared that a concentrated seabreeze-like convergence related to an ocean temperature gradient both sustained the cumuli, and superimposed itself on two outflow boundaries, so that two waterspouts appeared simultaneously, one on either side of the observing aircraft.

The role of the sea-breeze like convergence associated with strong SST gradients raises fascinating questions in connection with waterspouts. GATE oceanographers found similar ocean fronts on numerous occasions[4]. Woods[5] hypothesizes that they may originate by interaction between rainwater puddles with nocturnal convection and mesoscale jet streaks in the thermocline. In the waters off the Florida Keys and the Bahamas, surface temperature gradients are well known and pronounced. Golden

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[4]Personal communications from Feodor Ostapoff and John Woods.

[5]In a paper to be presented at the IUGG Conference at Hamburg, FRG in August 1983.

(1974, Fig. 7) noted preferred locations for waterspout formation associated with surface warm spots.

A most interesting question raised by the day 186 study concerns the spectacular concentration of the atmospheric convergence (~100 m) in comparison to the apparently much more spread out SST gradient (about 10-20 km). A high resolution version of a model such as that of Pielke (1974) could be used to investigate this interesting aspect of sea-air interaction. Also, a small research vessel equipped with water temperature thermistors and atmospheric boundary layer sounders similar to those used by Emmitt (1978) in GATE could inexpensively document relationships between SST's, low-level windfields, cumuli and possibly waterspouts in the Florida Keys.

Meanwhile, we hope to investigate the remainder of the GATE waterspouts in Table 1 with whatever data there are available and also to pursue further studies of the connective mechanism between the small surface whirls and the rotating cumulus cloud above.

ACKNOWLEDGEMENTS

This work could not have been conducted without the generous and extensive help of Drs. Joseph Golden and Edward Zipser who provided data, valuable analyses, enthusiasm and constructive criticism at all stages. The idea concerning the role of cumulus outflows in tilting low-level vortex tubes was evolved jointly with Professor Bruce Morton, with whom I plan a publication on waterspouts using the GATE cases as examples.

The writer is again grateful to the serendipity of NCAR pilot Gil Zinser for sighting the waterspout and to her GATE colleague Dr. Robert Grossman for photographing it, retaining the photograph, his notes, tapes and thoughts for nine years, which proved invaluable. Dr. Charles Warner provided the ship soundings and other excellent help. I am grateful to Drs. Robert Addis and George D. Emmitt for information on GATE gust fronts. Oceanographers Feodor Ostapoff and John Woods supplied fascinating material on ocean fronts and their possible genesis. Professor David Rodenhuis pointed out correctly that the simplified vorticity equation used could be solved analytically and the physical basis for its use explained better. Appreciation is owed to the numerous GATE participants (mostly listed in Table 1) who wrote or phoned me with their records of waterspouts seen and/or photographed.

Last but by no means least Goddard colleagues William Skillman and Cora Lee Sawyer carried out aircraft data analyses; Lafayette Long and William Skillman helped with the photogrammetry from the Electra films and Lafayette Long supervised production of all diagrams. Cora Lee Sawyer, Vicky Chin and Kelly Wilson typed the several drafts of the manuscript. Lee Dubach kindly served as Editor.

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APPENDIX

Cumulus Rotation: Model and Observations of a Waterspout-bearing Cloud System

J. Simpson

1 Introduction, Motivation, and Background Research

Intense cumulus rotation ha been found to precede severe tornadic storms. Substantial advances in documenting and understanding precursor conditions for destructive tornadic vortices have been made using Doppler radar observations. A typical tornado-associated "mesocyclone" has a diameter of 5-10 km, tangential wind velocities 15-25 ms^{-1} and vorticities in the neighborhood of 10^{-2} s^{-1}. Only about 60 percent of these strong mesocyclones produce funnels, however, suggesting that a special juxtaposition of a number of conditions is required.

Waterspouts appear to be similar, less intense atmospheric vortices, more accessible to measurement. This paper addressed the conditions required to produce a waterspout, using a three-dimensional cumulus model and observations made on a well-documented day (261) of the GATE[1] experiment of the Global Atmospheric Research Program. Primary emphasis is placed on the simulated development of cumulus-scale rotation. Second and more speculative emphasis is addressed to possible dynamic connections between the mesoscale rotation at intermediate cloud heights and the concentrated vortex funnel observed below cloud base.

Numerical model results (SCHLESINGER, 1978) and observations (HEYMSFIELD, 1981) show that rotation, usually in a cyclonic and anticyclonic vortex pair are the rule rather than the exception in cumuli growing in a windfield which varies with height. In particular, BLECHMAN's (1981) application of SCHLESINGER'S model, with no initial wind perturbation, shows mesovortex strength increases non-linearly with shear magnitude--rapidly at first and then levelling out at vorticity of about 10^{-2} s^{-1} when shear magnitudes reach about 1.5×10^{-3} sec^{-1} (in the layer 1-4 km with the same statically unstable thermodynamic sounding used by SCHLESINGER).

Two studies of the cumuli on day 261 of GATE have been performed with the same model using a precipitation scheme modified for tropical clouds. SIMPSON and VAN HELVOIRT (1980) simulated both the observed cumulonimbus and the cumulus congestus to investigate downdrafts, gust fronts and their impacts on the surface layer. The dependence of mesovortices on shear and their relation to organized entrainment was explored in further congestus model studies by SIMPSON, VAN HELVOIRT, and MCCUMBER (1981). The finding of mesovortices in all the model clouds,

[1]GATE stands for GARP Atlantic Tropical Experiment

Topics in Atmospheric and Oceanographic Sciences
Intense Atmospheric Vortices, ed. by Bengtsson/Lighthill

combined with recollection of an observed waterspout on GATE day 261 (one of two recorded on all 60 days of that field program) led to this effort to illuminate the combination of processes required.

2 Key Aspects of the Observations

The oceanic clouds and their surroundings in the study area on GATE day 261 were observed by five instrumented aircraft flying vertically stacked in a box pattern 150 km on a side. The northeast corner of the box, located at 10°N lat., 21°W long. contained a developing cumulonimbus system, which intensified while propagating slowly southwestward. Three of the GATE research ships were located just outside the box to the west and south, providing radar data, wind profiles (Fig. 2.1). thermodynamic soundings (Fig. 2.2) and boundary layer measurements.

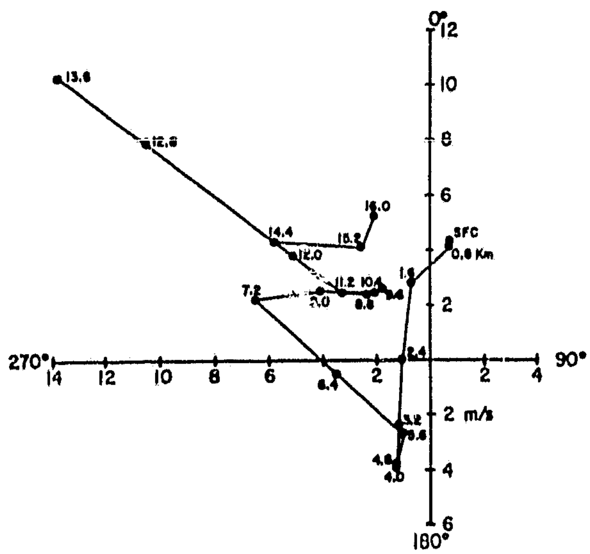


Fig. 2.1. Hodograph of observed wind profile near waterspout cloud on GATE day 261. Wind at any level is vector from center to level's image point

Fig. 2.3 shows the northeast corner of a detailed photogrammetric cloud map constructed from the aircraft films. Components of this map appear in extensive analyses of convection on this day (WARNER et al. 1979; 1980). The cloud heights (km) and locations agreed extremely well in comparison with both radar and satellite data.

The waterspout (Fig. 2.4) was captured on the side-looking cine camera of an Electra aircraft flying southward at 540 m elevation. The funnel was directly under the eastern edge of a congestus at the upshear end of a line flanking the cumulonimbus in Fig. 2.3. Restricted visibility prevented observation of the direction of funnel rotation. The congestus tower appeared stalled at about 7.8 km, as measured by a higher level aircraft (at 6.5 km elevation) just 2 min 50 sec before the funnel was

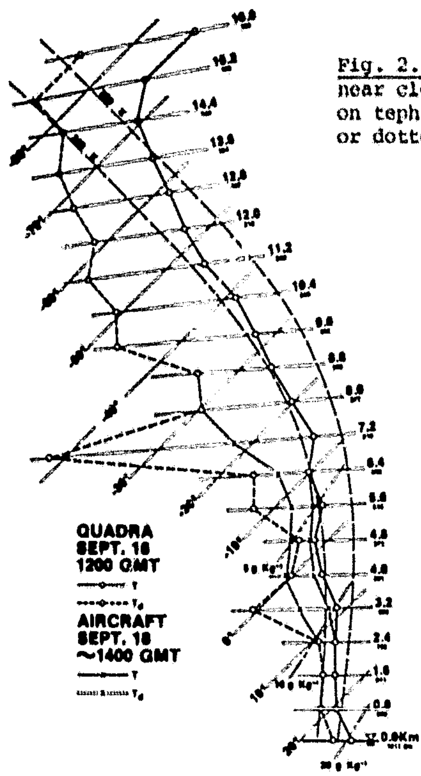
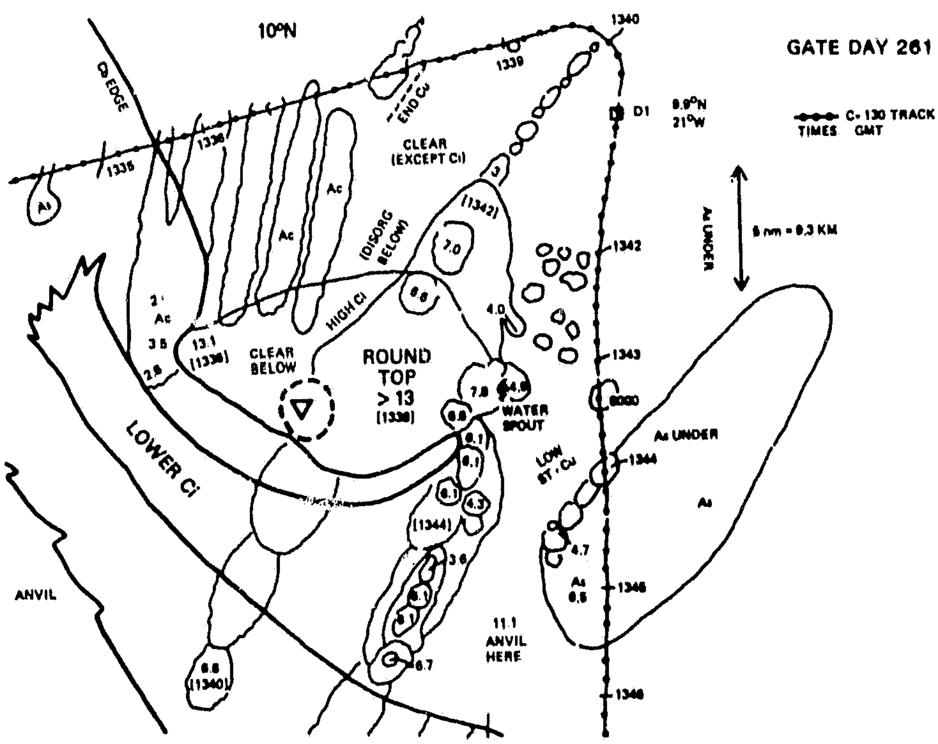


Fig. 2.2. Thermodynamic sounding at Ship QUADRA near cloud system at 1200 GMT day 261 plotted on tephigram. Solid line temperatures. Dashed or dotted dewpoint temperatures

Fig. 2.3. Portion of photogrammetrically constructed cloud map for cloud system near waterspout on GATE day 261. North upward. Four digit numbers times in GMT that C-130 (at 6.5 km) aircraft was at a location. Two digit numbers cloud heights in km



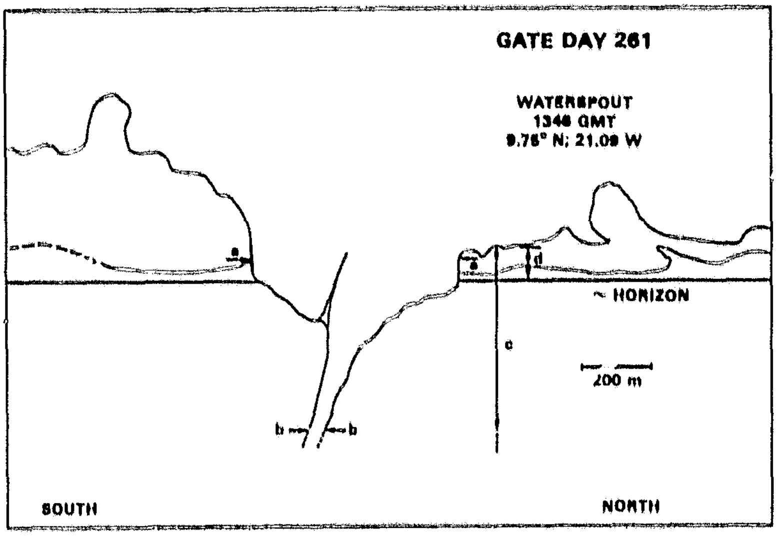


Fig. 2.4. Photogrammetrically constructed outline of waterspout from cine film on Electra aircraft flying southward at 540 m elevation. Waterspout diameter about 50 m

seen directly west of the Electra. The lower congestus towers at the upshear (northerly) end had a "boiling" appearance on the film, suggesting a more rapid rise rate than shown by members of the many congestus lines not associated with a cumulonimbus.

Typical significant features of the GATE cloud environment are 1) the stable dry lower cloud layer, which caused the rapid upward erosion of cumulus bases, and 2) the strong northerly wind shear between 0.8 and 4 km elevation (magnitude about $2.8 \times 10^{-3}\ s^{-1}$) which was previously shown to be essential for the mesovortex existence and orientation (SIMPSON et al. 1981).

Statistics on GATE cumulus updrafts (LEMONE and ZIPSER, 1980) reveal a sufficient condition for the rarity of waterspouts. Only 10 percent of the GATE updraft core sample exceeded $5\ m\ s^{-1}$, while Florida samples show updrafts more than a factor of two greater in the same percentile. Day 261 cumuli were active for GATE; both observations and models showed cores of about $6\ m\ s^{-1}$ in the active stage of both typical congestus and cumulonimbus. Therefore it is likely that the flow force is ordinarily too weak. The gross flow force F is defined (MORTON, 1969) as $\int_S (\rho w^2 + p)\, dS$ where w is updraft speed, p is dynamic pressure and S is any surface on a circumscribing circuit. A buoyant term must also be incorporated for warm flows.

A main hypothesis is that the alteration of the ambient thermodynamic sounding by the cumulonimbus in Fig. 2.3 shown by the x's in Fig. 2.2 enabled the nearby congestus to develop an updraft strong enough to provide the necessary funnel-sustaining flow force, although this condition is not regarded as sufficient.

3 Model Cloud in the Modified Environment

The modified version of SCHLESINGER'S 3-dimensional cloud model was run with the x'ed sounding in Fig. 2.2 and the same initial cylindrical perturbation used in the other congestus cases of SIMPSON et al. (1981). Figs. 3.1 and 3.2 show profiles of the invigorated model cloud. The updraft peak (~10 m s^{-1}) is stronger than that of either the congesti or cumulonimbi modelled with the unmodified sounding (SIMPSON and VAN HELVOIRT, 1980). The model tower top ascends at about 4 m s^{-1} in agreement with observed relationships.

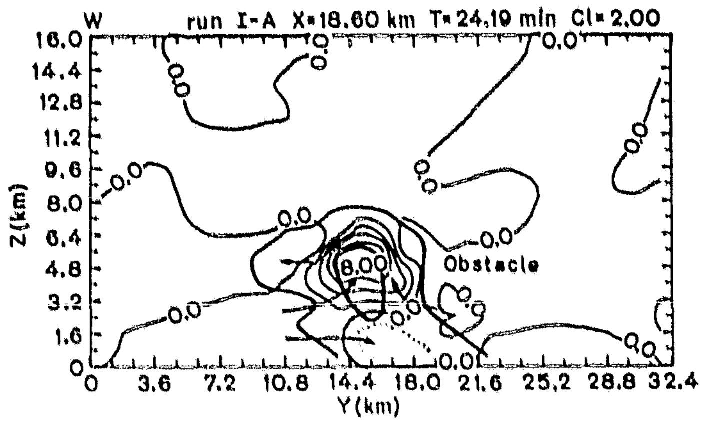


Fig. 3.1. Vertical profile through model waterspout-bearing congestus cloud in actively growing stage. Y-axis points north. Vertical velocities in m s^{-1}; each contour 2 m s^{-1}. Dashed line denotes downdraft. Heavy solid lines liquid water content, inner contour 3 g m^{-3}. Arrows indicate airflow relative to the cloud

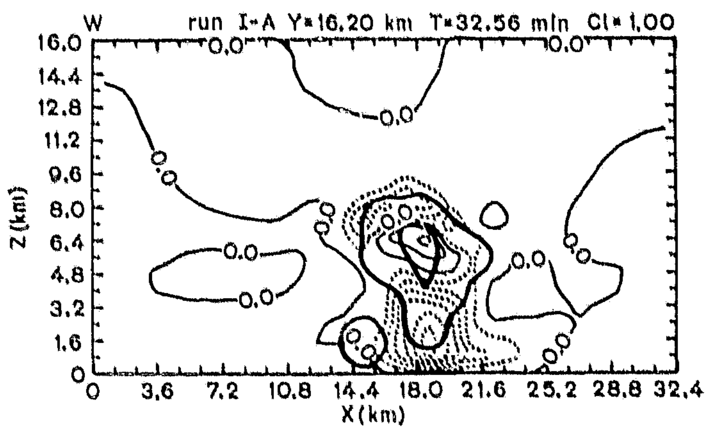


Fig. 3.2. Profile through same cloud 8 min after Fig. 3.1. Cloud top at maximum elevation. X-axis points toward east. Vertical velocity contours each 1 m s^{-1}. Dashed lines denote downdraft. Heavy solid lines liquid water, inner contour 1.25 g m^{-3}

In Fig. 3.1, if updraft velocity contours had been drawn at 25 cm s^{-1} instead of 2 m s^{-1}, the updraft extension to cloud base on the southeast side (rear, downshear flank) would have been apparent. Examination of the flow field relative to the cloud shows that its upper portions act as an obstacle toward relative flow from the north and east, while near cloud base the cloud acts as an obstacle to relative flow from southwest. Air is flowing into the downdraft (from the southwest) around the 2 km level, while it is entering the updraft (from both north and south) in the 3-4 km layer. By the time of Fig. 3.2 (8 min later) the updraft core has weakened to about 3 m s^{-1} and no longer has a downward connection to cloud base in the model. The lower portion of the model cloud is dominated by downdraft, with a core speed of 6 m s^{-1} at cloud base, which has eroded upward to about 1.2 km.

In the model cloud, precipitation reaching the surface begins at 20 minutes and terminates by 32 minutes. Rainfall is entirely confined to the northern half of the cloud and has shrunk to a tiny area at y=18 km by 24 minutes. On the aircraft film, no rain is seen falling from the base of the waterspout-producing cloud, although there are showers from the clouds to the south of it.

While the core updraft is only increased by one-third owing to the sounding modification, the flow force term containing the updraft is increased by 78 percent since it depends on the velocity squared.

The other postulated ingredients for waterspouts are examined next, before estimating the funnel time relative to the model cloud.

4 Cumulus Scale Rotation Related to Cloud Properties

Fig. 4.1 shows the vertical components of vorticity in the model cloud, as a function of time, at the level of strongest vorticities, namely 3.6 km. The peak value of 80 x 10^{-4} s^{-1} is in the range of mid latitude mesocyclones and two-thirds of the peak obtained by SCHLESINGER (1978) applying the model to mid-western severe storm conditions. A horizontal slice through the model cloud at 24 min (Fig. 4.2) shows the vortex pair at 3.6 km. All flow vectors are relative to the cloud motion, defined as the horizontal velocity of the center of gravity of the liquid water. The updraft core is split at this level with meso-anticyclone at the edge of the eastern (stronger) core and the mesocyclone collocated with the western (weaker) core. The meso-anticyclone tilts toward the south with height, but is continuous from cloud base to 6.8 km; the mesocyclone is continuous from 2 - 6.8 km, leaning more strongly to southeast. Both vorticity centers are within or at the edge of updraft from 2 - 6.8 km and one grid interval (1.2 km) or less away from updraft at cloud base. This is important because the funnel must be able to connect to the flow force (the rapidly rising tower). The vortex pair is strongest and most vertical in the layer 2 - 5.2 km, which is the layer of strong vertical windshear. It should be emphasized that the level of organization of vorticity in the cloud vortices reaches a maximum near the top of the shear layer extending from 0.8 to 4 km and then

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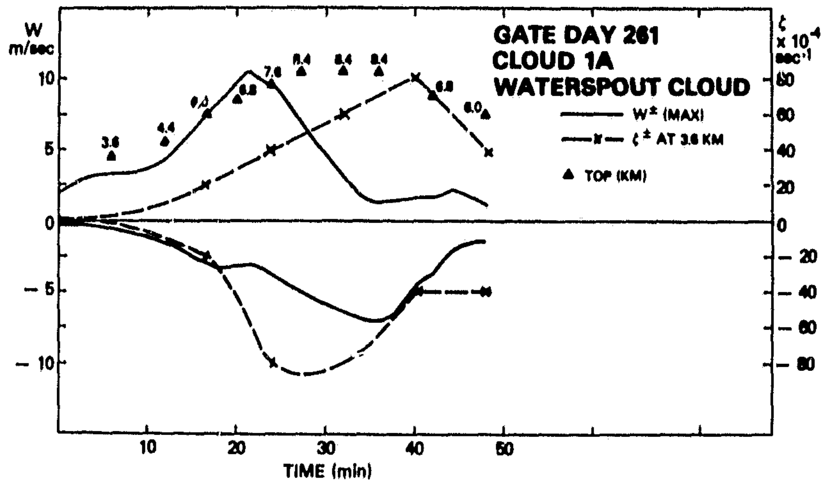


Fig. 4.1. Model cloud parameters as functions of time. Peak vertical velocities solid lines. Peak vorticities at the 3.6 km elevation ($x\ 10^{-4}$ s^{-1}) dashed lines. Cloud top in km denoted by triangle

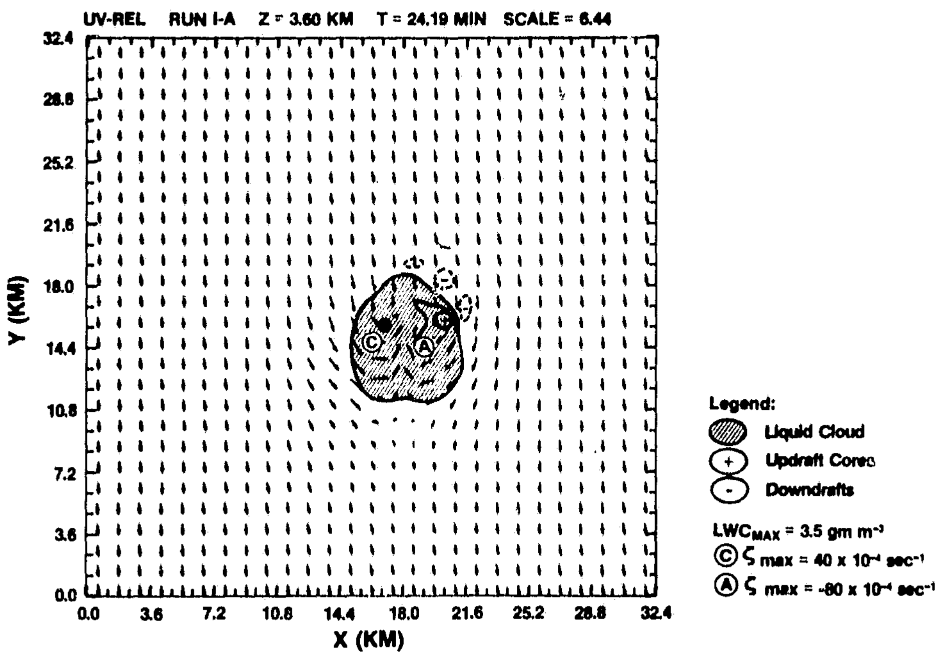
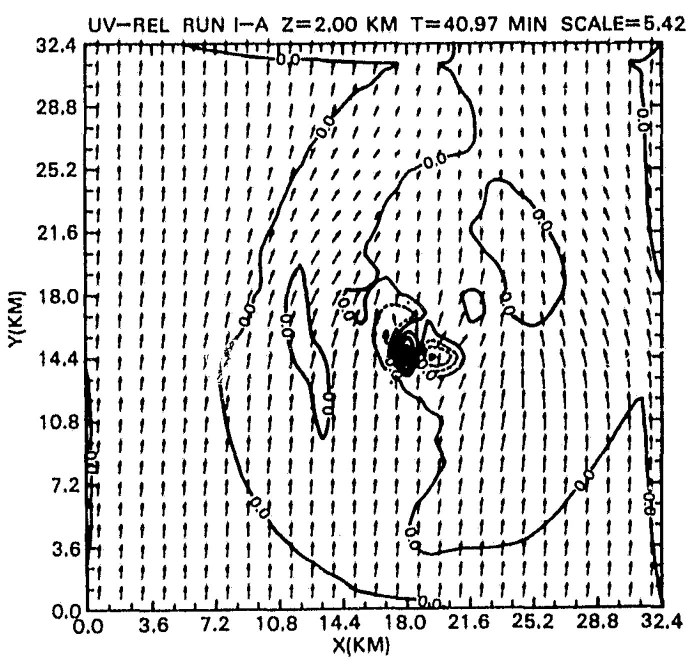


Fig. 4.2. Cloud-relative airflow at the 3.6 km elevation in active growth stage at 24 min. Longest arrow denotes relative velocity 6.44 m s^{-1}. C denotes center cyclonic mesovortex, A denotes center anticyclonic mesovortex. Plus signs show cores of split updraft ($w>4$ m s^{-1}); dashed lines containing minus signs denote downdrafts greater than 1 m s^{-1}. Hatched area liquid cloud

falls again as a consequence of diffusion without strong organization. The strong vortex layer also happens to coincide with the region of upward increasing updraft.

A horizontal slice through the cloud at 3.6 km, 8 minutes later than Fig. 4.2 (not reproduced) shows the cyclonic vorticity is stronger and the anticyclonic vorticity is about the same as previously, but the mesocyclone is within strong downdraft, while the meso-anticyclone is at the eastern edge of the downdraft, which now fills the model cloud up to 5 km (Fig. 3.2). Both vortices have little tilt at this time. The meso-anticyclone is in updraft at 5.2 km. The mesocyclone is within updraft at 6.8 km, but within downdraft at levels below.

At this time (32 min), the cloud tower has reached its maximum elevation, but has not yet started to descend. GOLDEN (1974) has observed waterspout funnels for a few minutes within obvious (precipitating) downdrafts. The mesocyclone peaks later and keeps extending further downward until after 40 minutes model time (Fig. 4.3). At the time of Fig. 4.3 (41 min) the cloud tower has just started its descent as the cyclonic vorticity peaks (Fig. 4.1). The mesocyclone is essentially vertical and is within weak updraft (1-2 m sec^{-1}) from cloud base level up to 5.2 km.



Vorticity Isopleths 10 x 10^{-4} sec^{-1}
Max Cyclonic = 40 x 10^{-4} sec^{-1}
Max Anticyclonic = 30 x 10^{-4} sec^{-1}

Fig. 4.3. Vorticity isopleths superimposed on cloud-relative airflow at 2 km elevation at 40.97 min model time. Longest vector is 5.42 m s^{-1}

A detailed examination of the terms in the equation for the vertical component of vorticity shows that the vortex pair is initiated by the tilting term. The vortices are intensified by the stretching or convergence term and advected vertically, upward at first and later down to cloud base as downdraft dominates the cloud increasingly after 32 minutes of model time. The downdraft also acts to intensify the vorticity by stretching.

Two factors are seen opposing a deeper, stronger, and less slanted vortex pair. The first is the rapid change in shear vector direction with height at 4.8 km, preventing the tilting term from helping the vortex pair develop at those levels. Second, the stable lower cloud layer typical of the GATE area causes the early appearance of downdraft in the lower cloud portions in both modelled and observed clouds. This causes the tilting term to oppose the vortex at low levels after a short time. In the Florida Keys, the lower cloud layer is more unstable, perhaps helping to account for more common and more intense waterspouts under similar or weaker windshear conditions. In the midwest, a very unstable lower cloud layer is coupled with shear, which only slowly veers in middle and upper levels providing the very strong mesocyclones found by Doppler radar.

5 Hypothesized Factors Related to Funnel Production

Florida waterspouts have measured circulation velocities of 4-35 m s^{-1} with diameters ranging from 7 - 150 m (GOLDEN, 1974; SCHWIESOW, 1981). Funnel vorticities are in the range 10^{-1} s^{-1} or greater. Highest vorticities found in midwestern mesocyclones are of the order 10^{-2} s^{-1} while the maximum in the model cloud was slightly less. The funnel on GATE day 261 measured about 50 m across so that even if its peripheral velocities were only 4-5 m s^{-1}, an order of magnitude larger vertical vorticity is still required than observed or modelled in cumulus-scale mesovortices.

There are no adequate mechanisms for spinning up a vertical component of vorticity of the order 10^{-1} sec^{-1} in the lifetime of a cumulus congestus cloud. We must, therefore, hypothesize that strong horizontal vortex tubes in the lowest boundary layer are suddenly tilted into the vertical. In neutral stability conditions over the oceans the logarithmic wind profile prevails, with shear vorticity (in the horizontal) of 10^{-1} s^{-1} or greater below about 10 m elevation and 1 s^{-1} or greater below about 1 m elevation. Adequate vorticity is clearly available.

On day 261, the boundary layer vorticity is associated with southerly flow increasing upward so that the vorticity vector points roughly westward.

The proposed tilting mechanism is the gust front from the neighboring cumulonimbus. Fig. 5.1 shows the lowest model level of the cumulonimbus, discussed in an earlier paper (SIMPSON and VAN HELVOIRT, 1980). The waterspout on the diagram is located by the observed distance between the waterspout and the cumulonimbus tower top. This estimates the waterspout location in the convergence zone and θ_E front associated with the model gust front.

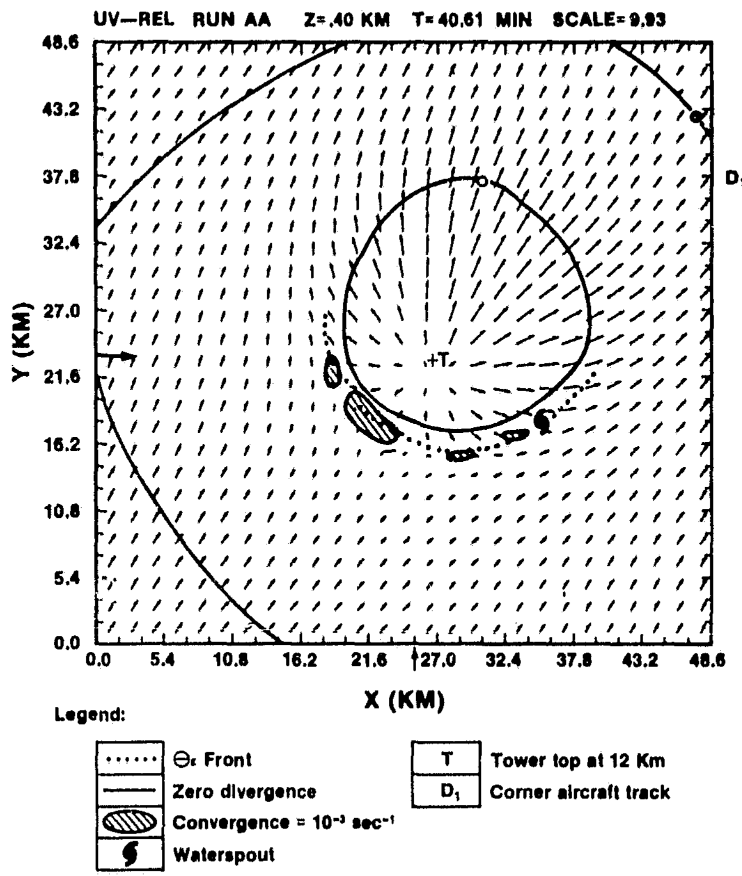


Fig. 5.1. Conditions below model cumulonimbus AA shown in Fig. 2.3 (further analyses in SIMPSON and VAN HELVOIRT, 1980) at mature stage. X-axis points east; Y-axis points north. Cloud relative airflow shown by vectors, largest 9.93 m s^{-1}. T denotes where observed cumulonimbus tower was located relative to observed waterspout location

The gust front is a wedge of cold dense air moving very slowly toward the waterspout location from about northwest. It can be envisaged as tipping bundles of the westward pointing vortex tubes upward into a vertical orientation so that the circulation around a tilted bundle is cyclonic (Fig. 5.2). GATE gust fronts on day 261 have been discussed by WARNER et al. (1981). Many (but not all) Florida waterspouts are observed on the upshear end of a congestus line flanking a cumulonimbus as in this case (GOLDEN , 1974).

The combination of the direction of boundary layer vorticity with the gust front location and motion appears to decide in favor of cyclonic rotation for the waterspout analyzed here.

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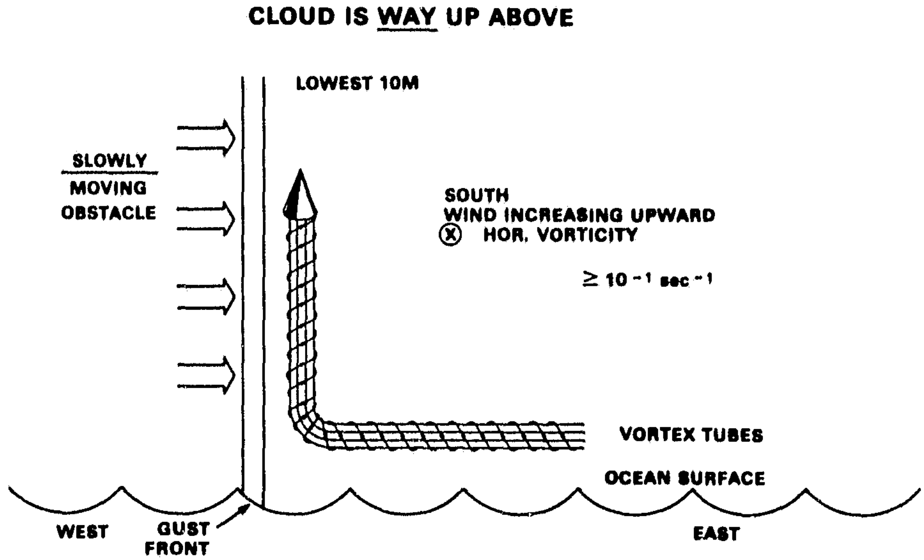

Fig. 5.2. Hypothesized upward tilting of vortex tubes in lowest boundary layer by gust front associated with cumulonimbus AA. Low-level vorticity associated with rapid upward increase of southerly wind just above ocean surface. Resulting cyclonic whirling postulated to connect with mesocyclone at cloud base producing visible funnel by rapid condensation

Other evidence favoring this hypothesis is that the waterspout-bearing cloud had "topped out" nearly 3 minutes prior to sighting the waterspout. Midwestern tornadoes are also found usually when the cloud tower is descending and when the mesocyclone has reached down to cloud base.

The above reasoning leads to estimating the time of the waterspout occurrence somewhere between 30-40 minutes cloud model time (see Fig. 4.1). An apparent problem is the weakened flow force and deep downdraft layer in the model cloud at 32 min; by 40 min the vertical velocity component of the flow is weaker still in the model cloud, although the mesocyclone is nearly vertical and in weak updraft up to 5.2 km. The difficulty here could be with the model, which was initiated with a non-repeating perturbation. Frequently, in real clouds a second thermal follows the first, or one may originate at mid-levels. It is also possible that the congestus just east of the water-spout rising through 4.9 km in Fig. 2.3 was providing some of the upward flow force at this time.

If the event sequence postulated here is on the right track, it becomes clearer why the dark spot is seen on the water first below the rotating cloud and the funnel is the last part of the system to appear. If the strong vorticity in the lowest 10 m or so is critical, intense whirling at the surface should appear before the funnel.

6 Concluding Remarks, Remaining Vital Questions and Recommendations for Further Work

It is concluded that most cumulus clouds in a shearing windfield will develop mesovortex pairs, hence areas of rotation, and that existing three-dimensional cumulus models are adequate to provide useful frameworks for synthesizing existing observations and for suggesting future observations. Improvements in the model ranging from microphysics, finer space resolution and different methods of initiation can make the simulations increasingly useful in examining important questions related to mesovortex evolution.

Many factors must coincide in space and time for an adequate mesovortex to exist at cloud base, connected upward to a convective flow force and downward to a suddenly tilted bundle of vortex tubes in the lower boundary layer. For the waterspout on GATE day 261, it seems that the nearby cumulonimbus was essential in two ways, first to strengthen the flow force and the mesocyclone via intensified updraft, and second to provide a steep density current (gust front) at just the time and place where the mesocyclone had reached cloud base. With the short active lifetime of GATE clouds relative to those in the Florida area, owing to the more stable lower cloud layer, it is not surprising that the "window" for coincidence of the necessary factors is short, and so waterspouts are quite rare in the GATE area.

A cloud which has a longer active lifetime of its updraft could use its own gust front to "scoop up" surface vorticity. This must be the case with those isolated waterspout-bearing cumuli off the Florida Keys; evidence (LEMON and DOSWELL, 1979) is similar for tornadic storms where updrafts and downdrafts may coexist side-by-side.

Major questions not addressed in this paper are 1) how the "scooped up" vortex tube bundle suddenly connects upward with the mesocyclone (and thence the flow force) which must involve pressure forces, and 2) what factors determine the scale of the funnel. These problems are probably better addressed in laboratory experiments, theoretical analyses and model simulations (e.g., SMITH and LESLIE, 1979).

Further observations are, however, required of waterspout-bearing cumulus clouds. The highest frequency in an accessible area is undoubtedly the Florida Keys where GOLDEN'S and SCHWIESOW'S find work should be followed up with the improved measuring systems now available. In particular, the in-cloud motion field needs to be measured as a function of time to relate updraft/downdraft structure to rotation. Fortunately, maritime cumuli in the Floirda area usually have plentiful precipitation particles inside them by the time they have grown to 3-4 km elevation so that Doppler radar could be used, which would be particularly valuable if airborne and so enabled to "chase" clouds.

A lower-flying aircraft carrying the Doppler lidar effectively used by SCHWIESOW (1981) could relate the waterspout properties to the associated cloud mesovortices above. Ambient wind and thermodynamic profiles might be obtained by aircraft drop-

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windsondes or boundary layer profiling systems as in the GATE. If resources were very limited, winds obtained by a network of pilot balloon releases together with time-lapse camera sites could provide the minimum additional essential information.

7 Acknowledgements

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