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WATERSPOUTS AND TORNADOES OVER SOUTH FLORIDA[1]

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ABSTRACT

An analysis of the Lower Matecumbe Key 1967 waterspout data is presented. It was found that the flow field synthesized across the spray vortex of the second, larger waterspout is closely approximated by a Rankine-combined vortex with solid rotation over a circle 24 m in diameter. Five major tornadoes were documented in the Greater Miami area during 1968, and this anomalous number is ascribed to the development of strong localized zones of convergence on the mesoscale along or slightly inland from the southeast coast where the prevailing southwesterly tropospheric flow interacts with the sea breeze induced by the Florida Peninsula. On the other hand, the large number of waterspouts documented in the Lower Keys during the summer of 1968 were spawned by cumulus congestus cloud lines embedded in a very warm undisturbed trade-wind flow.

Extensive documentation of close-range observations was obtained for an unusually large "tornadic waterspout" that passed through a crowded coastal marina in Miami. Evidence concerning the formation process, flow kinematics, and the problem of a "flying houseboat" are presented.

1. INTRODUCTION

What is a waterspout? Is it just a tornado over a water surface (as defined in the *Glossary of Meteorology*, Huschke 1959), or is there some fundamental difference in structure and energetics? We cannot be sure; but for purposes of this discussion, a waterspout will be defined as an intense columnar vortex (usually containing a funnel cloud) of small horizontal extent that occurs over a body of water. We emphasize that, at least for waterspouts over South Florida, rarely does the visible funnel extend all the way from the parent cloud base to the sea surface. As in the case of the tornado, most of the waterspout funnel is thought to become visible by condensation of water vapor. The visible funnel's outer surface would then outline the surface of constant-isentropic condensation pressure.

While tornadoes are most often associated with cumulonimbus activity, waterspouts may originate from "trade cumuli, with tops not higher than 12,000 ft" (Riehl 1965). Furthermore, waterspouts have been reported reliably as pendant from shallow stratocumulus clouds. The classical tornado occurs in the right rear flank of squall lines or in an air mass with pronounced low-level instability and vertical wind shear. Both of these last two conditions are *typically absent* from the environment of the South Florida waterspout; indeed, the air mass in this region during the summer is usually homogeneous in the horizontal and stable, with very weak vertical wind shear. The evidence is that the major observed differences between the *average* land tornado and the *average* large waterspout are *intensity, duration, and translational speed.* Morton (1966) and others, in accounting for these differences, stress the *different flow termination over ground and water*. Brooks (1951) emphasized the importance of the lower boundary by noting that waterspouts often dissipate on reaching a shoreline. It was observed by the present author (Golden 1968) that the first of two waterspouts that made landfall on the south shore of Lower Matecumbe Key on Sept. 2, 1967, soon afterward resembled a large dust devil. The circulation at low levels decreased rapidly after moving overland, and the visible funnel expanded, became very hollow and translucent, and gradually retracted into the parent cloud. However, this average-sized waterspout maintained its vortical identity while crossing some 1,100 yd of flat land and reformed after moving off the north shore of the Key.

A literature on waterspouts is virtually nonexistent, and there are few guidelines for research on the problem. By far, the majority of the work on this subject comprises individual observations of waterspout occurrence from the surface, a few documented by still photographs or drawings constructed from memory. Perhaps one of the best early comprehensive surveys of waterspout structure and behavior, deduced from observations available up to that time, was made by Ferrel (1893) in his *A Popular Treatise on the Winds.* There remains much disagreement over certain structural features of the waterspout, particularly the sense of vertical motion in and surrounding the funnel. Vortex structure within the parent cloud is completely unknown. Some of the more plausible waterspout models deduced from surface observations have been proposed by Bundgaard (1953), Dinwiddie (1959), and Rossmann (1960). These are shown in figures 1–3 and illustrate some of the contrasting models of waterspout structure and radial-vertical circulation. The only estimate of the pressure minimum in a waterspout was given by Chollet (1958). He describes a ship being overtaken by a waterspout during which the ship's barometer fell 21 mb.

Theoretical studies have taken the form of laboratory modeling and numerical diagnostic models. One of the more interesting laboratory experiments was performed

[1] See also Golden (1968).

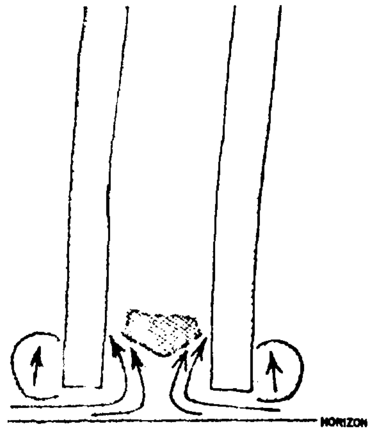

FIGURE 1.—Waterspout model from Dinwiddie (1959).

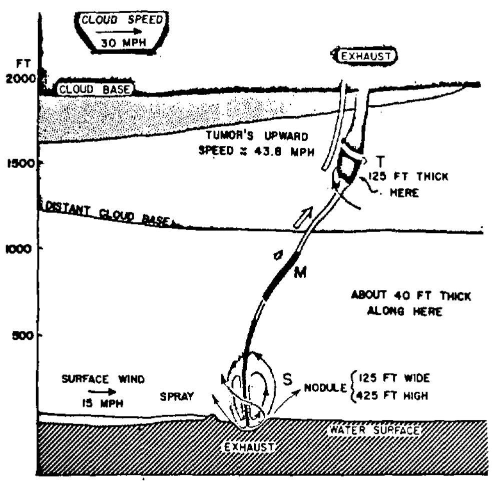

FIGURE 2.—Schematic waterspout flow model made from the frame of a 16-mm telephoto movie taken of a 1953 Tampa Bay waterspout by Bundgaard (1953).

by Turner and Lilly (1963). The release of buoyancy by condensation in the atmosphere was modeled by using the release of gas bubbles in carbonated water set in solid rotation. These experiments and those of Rosenzweig et al. (1962) indicate that the interaction with the upper and lower boundary layers is very important.

Current numerical models of tornadic vortices agree that their formation is related to the concentration of pre-existing angular momentum by convective processes. Early numerical solutions were generally of the "one-celled" Burgers (1948) type or the "two-celled" Sullivan (1959) vortex, the latter yielding flows with an axial stagnation point at the ground or some distance above it. These solutions become much more realistic when thermal effects are taken into account, as done by Gutman (1957) and Kuo (1966). Their numerical models contain buoyancy terms and produce more realistic appearing flow fields, but do not contain any effects of the frictional drag of the lower boundary on the flow components. Further progress in both the numerical and laboratory-modeling approaches is hindered by the lack of any quantitative observational data with which to check them.

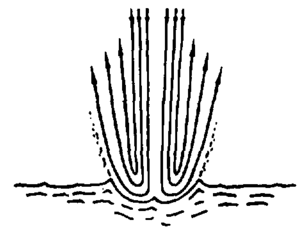

FIGURE 3.—"Streamline divergence at the base of a waterspout and shape of the sea surface . . . gives schematically the flow pattern of a water-spout foot: A depression in the water surface or a ring-shaped wave, the crest of which breaks up in water droplets and forms the water spray around the funnel" (Rossmann 1960).

PRIMARY OBJECTIVES

Of the many questions that invite attention to the waterspout, the following represent the interest toward which this study is directed:

1. Is this vortex mechanically forced, or is it a thermally induced quasi-hydrostatic system?
2. What is the environmental setting favorable for waterspout formation?
3. Is the vertical flow in the vortex driven by buoyancy, friction, or axial pressure gradients due to the development of a concentrated core?

2. ANALYSIS OF THE LOWER MATECUMBE KEY WATERSPOUT OF SEPT. 2, 1967

During a chance aerial encounter near Lower Matecumbe Key, Fla., a series of three waterspouts were documented at close range over a period of 35 min. When using a high-resolution super-8 movie camera with 5:1 zoom and bayonet-type slide camera, the approach, landfall, crossing, and reformation of the first small waterspout over the Key was recorded. The aircraft flew in a tight anticyclonic circle and descended from 2,000 to 800 ft MSL to obtain detailed observations on the structure and kinematics of the second, larger waterspout, especially the lower portion made visible by sea spray. Cloud base and the aircraft's altitude were determined from the pressure altimeter setting, and the tops of the north-northeast–south-southwest line of cumulus congestus clouds that spawned the waterspouts were estimated at near 20,000 ft. The circumstances leading up to this aerial encounter and its documentation appear in a preliminary article (Woodley et al. 1967) and later in more complete detail (Golden 1968).

Soundings taken at Miami and Key West, 1½ hr later and each 60 n.mi. away from Lower Matecumbe Key, indicate that the air mass over the Keys was quite homogeneous at the time and place in question. The Key West sounding (Golden 1968) shows an air mass typical of

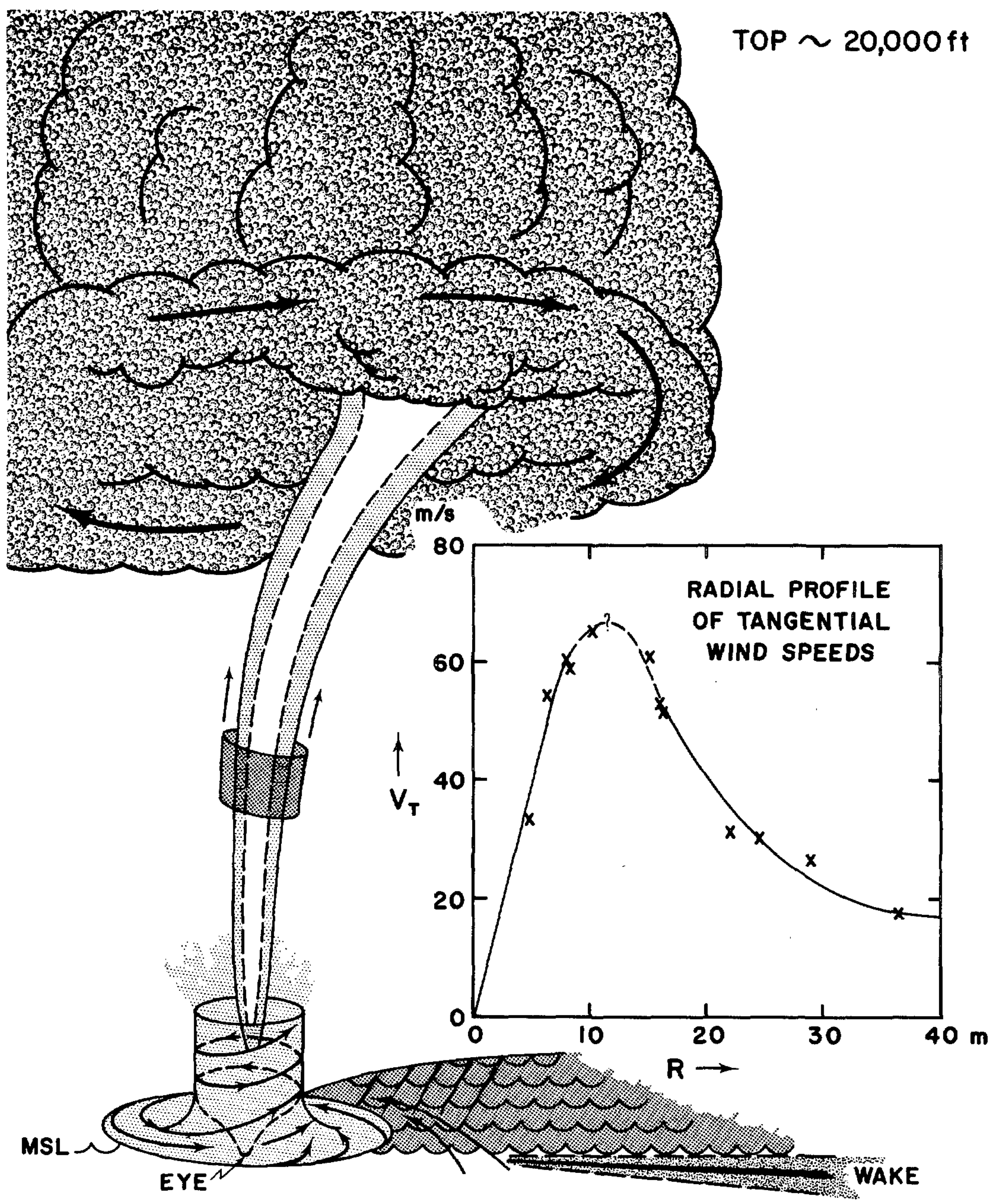

FIGURE 4.—Proposed three-dimensional structure model of a waterspout based on detailed aircraft observations of the Lower Matecumbe Key waterspouts at close range. The vertical scale is greatly contracted. The inset shows the derived radial profile of tangential speeds through the waterspout's spray vortex. Note the trailing "wake" of disturbed sea water, with the wave train oriented perpendicular to and on the right side of the wake (cyclonic waterspout). For details, see Golden (1968).

undisturbed trade flow, with no pronounced subsidence inversions and weak vertical wind shear in the lowest 20,000 ft.

Photogrammetry with use of the slides revealed that the largest waterspout funnel varied in diameter from 125 ft near the parent cloud base to 70 ft at its lower end. Using the dimensions of the surface spray vortex obtained with the slides and then tracking and timing the rotation of spray plumes and particles at various radii, we obtained a tangential velocity profile through the spray vortex.

The resulting three-dimensional model synthesized from data on the two major waterspouts is shown in figure 4, which includes an inset showing the measured tangential speed profile across the spray vortex of the most intense waterspout. Subsequent data gathered by the author lend additional support to this model. The reader should compare figure 4 with the earlier models given in figures 1–3.

The derived tangential wind-speed profile through the waterspout's spray vortex closely approximates that of a *Rankine-combined vortex*. With the ordinate axis as tangential wind speed (V_T) in meters per second and the abscissa as radius (R) in meters, we note that the maximum tangential wind speed is 65.0 m s^{-1} or *130 kt at a radius of just 12 m from the center.* This profile and maximum tangential wind speed should be compared with Hoecker's (1960) analysis of the Dallas tornado film. In the latter, a composite distribution of tangential and upward components of the air flow around the Dallas tornado was determined by tracking debris particles, dust parcels, and cloud tag movements in scaled movies. (Doubts may be raised here as to how well solid debris, such as sheet metal or lumber, responds to the air motion.) When using this method, the greatest derived tangential speed was 170 mi hr^{-1} at a radius of 130 ft and an elevation of 225 ft. Looking at figure 4 again, we note that the profile derived from the Lower Matecumbe Key film is really the vertically averaged tangential speed distribution across the uppermost layers of the spray vortex. The average depth of the spray vortex is about 50 ft.

In atmospheric dynamics, it is often assumed that the cyclostrophic wind is a valid approximation to the real wind in tropical cyclones in equatorial latitudes and in small-scale vortices with very great wind speeds and path curvature (e.g., Hoecker 1961 and Long 1958). Having derived a profile of tangential wind speeds through the spray vortex of a large waterspout (fig. 4), one should be able to integrate the cyclostrophic wind relation from the outer edge of the spray vortex ($R=36.5$ m) inward to its center and thereby obtain the total pressure drop across the vortex. We may write the cyclostrophic wind relation as

$$\frac{V_c^2}{2}=\frac{1}{\rho}\frac{\partial p}{\partial r}.$$

By using the characteristics of the derived profile discussed earlier, the above relation was integrated with respect to radius in two steps: (1) from $R=36.5$ m inward to $R=12$ m (the speed maximum) and (2) from $R=12$ m to the vortex center. The value of density used was that for saturated air with an adjusted virtual temperature, from synoptic data at Key West International Airport. *The total pressure drop across the spray vortex was 44.3 mb, giving a central pressure of 971 mb. All but a few percent of the total pressure drop occurred from the outer edge of the spray vortex inward to the speed maximum.* A total pressure drop at the ground of almost 60 mb was found for the Dallas tornado of 1957, by an integration of the cyclostrophic wind equation (Hoecker 1961). Hoecker suspected that this figure is a conservative estimate of the actual surface pressure drop, since most of his wind speed values were derived during an immature stage of the tornado.

A "spray sheath," concentric with and outward from the visible funnel and rising from the sea surface, has been documented from these recent data. For the large Lower Matecumbe Key waterspout, the spray sheath had a diameter of 130–150 ft (fig. 4). The spray sheath is an important feature because it outlines an annulus of intense rising motions surrounding the visible funnel and extending upward (in this case) to 400 ft MSL. The upward extent of the spray sheath in any given waterspout would depend upon the terminal velocity of the size spectrum of spray droplets carried helically aloft and the balancing rising motion. The ring of maximum tangential winds occurs at a radius just outside the "eye" region on figure 4. In figure 4, the wind profile has been dashed in the region of the speed maximum—in this region on the film is a very bright ring of rapidly circulating spray. Precise photogrammetric measurements of the shape of the wind profile in this region with the projection equipment available were most difficult. However, we stress the fact that those points plotted on the profile were carefully checked and *were found to be reproducible* with a different member of the team performing the spray tracking. Any questionable data points on the original profile derived by photogrammetry have been eliminated in this version. When allowing for errors in tracking spray particles and plumes in the maximum region, the maximum of 130 kt is considered correct within 10 percent, probably on the low side.

We return to a question raised earlier. What are the dynamical implications of this wind profile for the circulation in the waterspout's spray vortex? Consistent with the Rankine-combined nature of this vortex, we note that, inward from the speed maximum near 12 m, the air-spray mixture is in *solid-body rotation* with a near-linear decrease of speed inward to the vortex center. In this region, a parcel subject to displacements will conserve its angular momentum and tend to remain at the same radius (be dynamically neutral). Outward from the speed maximum, the air-spray circulation becomes *irrotational*, and the derived profile fits the theoretical curve $VR=$const very well. These results compare favorably with the simplified theory and observational deductions made by Glaser (1960) using a still photograph of a tornado.

3. RECENT WATERSPOUT-TORNADO EVENTS OVER SOUTH FLORIDA: FIVE "DIRECT HITS" IN GREATER MIAMI DURING SPRING AND SUMMER OF 1968

Figure 5 shows an enlarged map of Miami and vicinity, with plotted tracks and dates of tornadoes that struck the area during this century. From the total of seven, the following five tornadoes occurred during 1968:

1. February 19—touched down at about 0550 EST in northern Dade County and tore through the suburb of North Miami Beach at 40 to 50 mi hr^{-1}, doing severe damage.

2. June 7—was an unusually large "tornadic waterspout" that ripsawed through the Dinner Key boat marina in midafternoon. Evidence as to the formation process and a proposed physical mechanism for the observed damage will be presented in the next section.

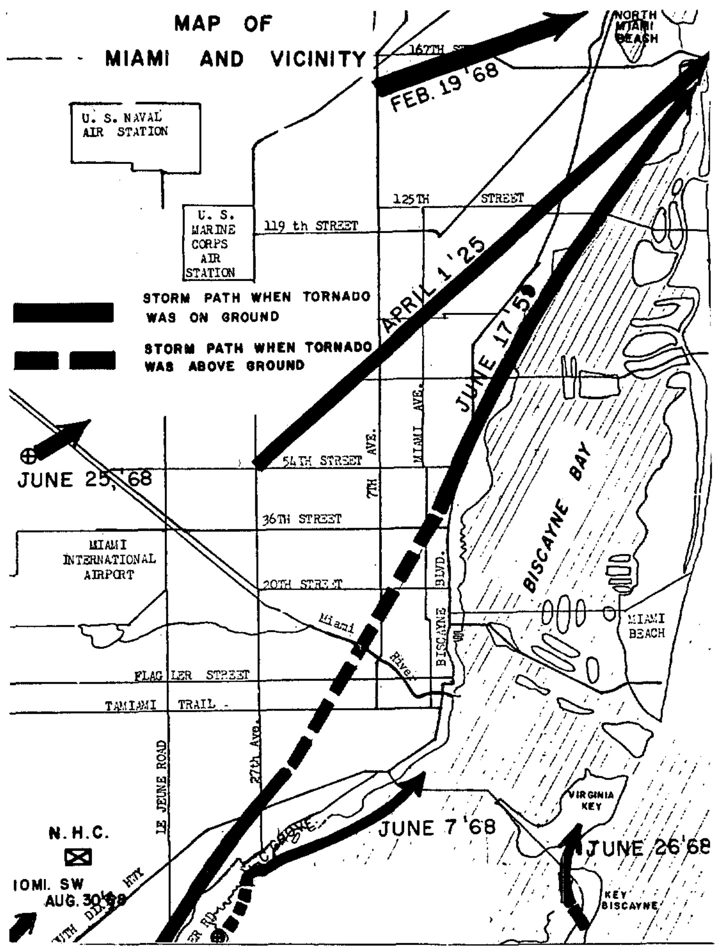

FIGURE 5.—Map of Greater Miami with the tracks of seven authenticated tornadoes that struck the area in this century, through 1968. Five of these occurred in 1968.

3. June 25—was a small ropelike tornado that touched down at 1825 EDT about 1 mi west of the airport and continued northeast at about 15 mi hr^{-1} through portions of Miami Springs and Opa-Locka.

4. June 26—was a large destructive tornado that formed over Key Biscayne during a predawn thunderstorm and overturned or sunk six cabin cruisers in a marina.

5. August 30—was observed during the midafternoon about 10 mi southwest of the National Hurricane Center. A very long funnel skipped along freshly plowed fields in sparsely populated suburbs of Miami.

We have listed these five major events not only because they represent a unique departure from climatology for the Miami-South Florida area but also to examine the unusual and distinct character of tornadoes that occur in this locale.

One might well inquire at the outset as to the synoptic scale and mesoscale circulation features accompanying this unprecedented number of tornado outbreaks. With the exception of the February tornado, which formed in *air-mass thunderstorms* in the warm sector of a frontal wave, all the others occurred during the summer. In addition, the last four tornadoes were spawned in "air-mass thunderstorms" (organized in the mesoscale) that developed within a nearly *homogeneous mT* air mass, without the benefit of any mid-latitude fronts or upper level jet stream. In all cases, developing thundershowers were present with radar tops *initially* at 25,000 to 30,000 ft. Evidence has accumulated to show that the parent thunderstorm in all five cases was *growing appreciably in the vertical* at the time of tornado development; and, eventually, cloud tops of 40,000 to 50,000 ft were measured by the Miami WSR-57 (weather surveillance radar), in the latter four cases.

Along with the summertime tornadoes in Miami, about 39 waterspout sightings were documented in the Key West area by Clemons (1969) for the period May through October 1968; within this same period (June 6 to October 15), Rossow (1969) documented 79 waterspout sightings in the Lower Keys, most of them from a Navy aircraft aloft. Among these, we have since learned that there were at least seven, large potentially destructive waterspouts within 30 n.mi. of Key West (Rossow's waterspouts were all estimated to be 10 m or less in diameter). These statistics provided some of the impetus to the summer of 1969 field program outlined in section 5.

What then are the physical processes responsible for this anomalous number of documented tornado-waterspout events in the Greater Miami and Key West areas? Certainly, increased public concern and awareness and the vigorous observational programs of Clemons and Rossow account for most of the Key West waterspout sightings. Of prime importance, however, is the fact that the 3-mo period of May, June, and July 1968 was the rainiest in Miami's recorded history. Normally rainy June set a record in itself. The interested reader is referred to Stark (1968), Green (1968), and Wagner (1968) for a discussion of the weather and synoptic scale circulation features over Florida during each of these 3 mo, respectively. During all five tornado developments, the flow in the low troposphere to the mid-troposphere was southwesterly to westerly. Three of the tornadoes occurred during the afternoon and early evening hours. With the pronounced daytime heating predominant over the Florida Peninsula during the summer months, the moist convective air mass was sufficient to produce locally heavy afternoon and evening thundershowers along the southeast Florida coast. *Strong localized zones of low-level convergence on the mesoscale frequently develop along or slightly inland from the southeast coast where the anomalous westerly flow interacts with the sea breeze induced by the Florida Peninsula.* (See the radar-echo study of Frank et al. 1967 and the numerical sea-breeze experiment of Estoque 1961.) The type of prevailing flow pattern described here occurs in short intermittent intervals during the spring and early summer months; however, its presence over a nearly continuous period of several weeks constitutes a climatological singularity and accounts for the record rainfall observed.

FIGURE 6.—This view looking south from downtown Coral Gables was taken by an eyewitness during the final descent of the Dinner Key tornadic waterspout from its parent collar cloud.

4. THE "FLYING HOUSEBOAT": A PROPOSED PHYSICAL MECHANISM FOR THE OBSERVED DAMAGE

A large funnel cloud was sighted over land on the coast about 2 mi southeast of the National Hurricane Center at 3:10 p.m. EDT on June 7, 1968. The funnel dipped down briefly over a wooded area, churning up leaves and small branches, and then retracted back up into the parent cumulus congestus cloud line. About 5 min later, the funnel touched down for the final time *over water* at a point just southwest of the Dinner Key piers (fig. 5). Figure 6 is a photograph taken at about this time by an eyewitness 2 n.mi. north of Dinner Key. Note the distinct collar cloud that spawned this tornadic waterspout—it resembles in many respects a similar structure noted by Fujita (1960) in the Fargo tornado of 1957. About 10 min prior to the taking of figure 6, eyewitnesses told of watching three rapidly whirling cyclonic eddies rotating about the center of the collar cloud. Rough photogrammetric calculations indicate a diameter of 2,000 ft and a thickness of 1,200 ft for the collar cloud. Finally, 5 min prior to the funnel descent shown in figure 6, the three eddies suddenly amalgamated; and the collar cloud itself began to rotate bodily in a cyclonic sense. Photographs taken later of the fully formed tornado yield a funnel diameter of 250–300 ft just below the collar cloud.

We have labeled this rare phenomenom a "tornadic waterspout" after Morton (1966). In this case, tornado formation first took place over land, *but most of its 35-min lifetime was spent traveling on the water surface of Biscayne Bay while maintaining great intensity.*

Of particular interest here is a houseboat (35 ft by 14 ft and weighing 5 tons) that was carried 6 to 10 ft above water from its moorings at the second pier at Dinner Key. The houseboat (fig. 7), fortunately with no one aboard, was carried around the rear of the vortex circulation where it landed on its side, impaled on an 8-ft wooden piling some 100 ft away from its berth. A detailed analysis of the storm's track and documented damage at Dinner Key is given in a recent article by the author (1969*b*).

FIGURE 7.—Longitudinal view of a 5-ton houseboat after a tornadic storm passed through Dinner Key, Fla., piers. The houseboat was lifted 6–10 ft out of the water from its moorings, carried 100 ft down the pier, and finally dropped and impaled on an 8-ft wooden piling.

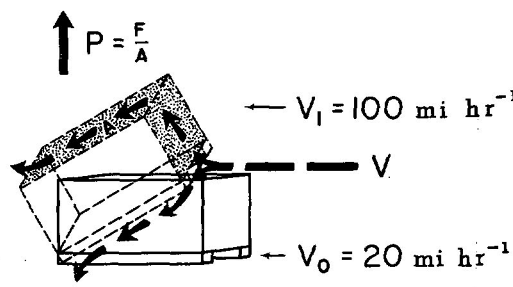

FIGURE 8.—Schematic diagram illustrating the proposed two-step physical mechanism for lifting the houseboat from the water. The dimensions of the houseboat (fig. 7) were specifically 10 ft by 14 ft by 35 ft, weight $(F)=5$ tons. The upper surface area A after tilting is stippled.

Although Hoecker's (1960) analysis of vertical motions around the Dallas tornado imply very large values of dW/dZ just above the surface, vertical motions alone could not have initially lifted the houseboat clear of the water. Some other mechanism must be invoked. What we propose here is a two-step solution to the problem, the physics of which is diagramed in figure 8.

1. Initially, the underbelly of the houseboat, which was resting on pontoons running along each side, was reported to be about 6 in. above the water surface. When allowing for some momentum to be imparted to the sea surface, a sufficient rate of increase of horizontal wind with height to above 10 ft would have provided torque

to tilt the houseboat up from its initial horizontal position. The new orientation of the houseboat, with its upstream end raised free of the water, is shown by dashed lines in figure 8. Note that, at this instant, the houseboat assumes an airfoil-like shape relative to the airstream.

2. We apply the airfoil theory of hydrodynamics and Bernoulli's equation. The latter applies to the pressure differences that accompany acceleration in the airstream. This equation defines the pressure at points along the same streamline where the velocity is different. The airfoil-like shape of the houseboat embedded in a flow of velocity V would induce, by its presence, acceleration of the flow to $V+\Delta V$ across its upper surface. This would be accompanied by a pressure change of $P-\Delta P$ across the upper surface and resultant upward force $A\Delta P$ (assuming no change in velocities and pressures across the lower surface). We therefore write Bernoulli's equation as

$$\frac{P_0}{\rho}+\frac{1}{2}V_0^2=\frac{P_1}{\rho}+\frac{1}{2}V_1^2+gz_1.$$

We must estimate V_0 and $V_1=V+\Delta V$, the velocities at the lower and upper surfaces, respectively. At the underbelly of the houseboat, $z\ll z_1=20$ ft, $V_0\doteq 20$ mi hr^{-1}, and $P=P_0$. When solving for the total vertical pressure difference, P, between the upper and lower surfaces of the houseboat as shown in figure 8,

$$\Delta P=P_0-P_1=\frac{1}{2}\rho(V_1^2-V_0^2)+\rho g z_1.$$

Using synoptic data taken at the Miami International Airport, we first computed the virtual temperature; and from that, $\rho=0.00117$ g cm^{-3}. After careful inspection of the damage and eyewitness accounts and photos from the Dinner Key marina, it is believed that the maximum tangential speed in the tornadic waterspout there lies somewhere between that derived for the Dallas tornado and the Lower Matecumbe Key waterspout. We therefore assume $V_1=100$ mi hr^{-1} at $z_1=20$ ft with the maximum attained at some higher elevation. We thereby obtain

$\Delta P=(11.23+0.70)\times 10^3$ d cm $^{-2}=$ *11.93 mb* (d for dynes).

This quantity represents the total vertical pressure differential acting between the upper and lower surfaces of the tipped houseboat for the estimated induced wind velocities. Knowing that the houseboat was lifted free of the water, we can independently compute the force per unit area of the upper surface necessary to just balance the 10,000-lb weight. We solve for the

$$P=F/A=5.86\times 10^3 \text{ d cm}^{-2}=5.86 \text{ mb}.$$

Note that the vertical pressure differential computed above from Bernoulli's equation is just about twice that required to balance the houseboat's weight. We note in closing that the houseboat was located just to the left of the track of the tornadic waterspout as it crossed the pier diagonally. Data examined in Golden (1969*b*) show that relative to the moving vortex, the houseboat was in a region of *strongly accelerating shallow inflow* at the time of its lift. The simple computational results above seem quite reasonable, considering our neglect of surface tension, turbulence, wind-gust factors, etc.

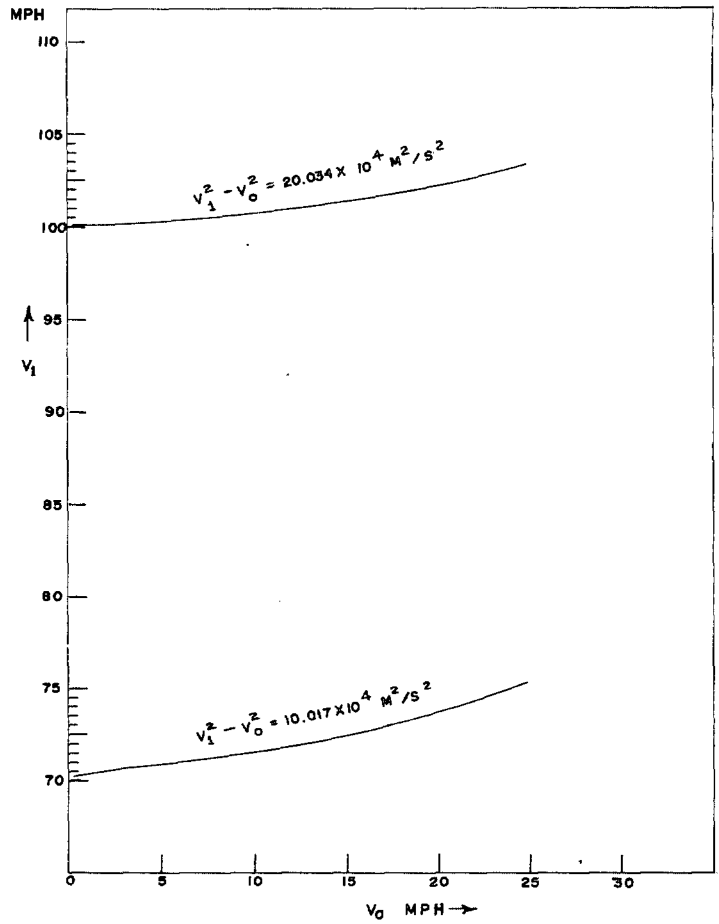

FIGURE 9.—Graph of V_1 versus V_0 for the value of the term $V^2-V_0^2$ (lower curve) and for twice this value (upper curve).

We have found that a 5.86-mb pressure differential is sufficient to just lift the houseboat out of the water. We therefore substitute $\Delta P=5.86$ mb in the left side of Bernoulli's equation and find that $V_1^2-V_0^2=10.017\times 10^4$ m^2 s^{-2}. Refer to figure 9 that illustrates the physical possibilities not subject to easy analysis without a wind tunnel. The lower curve shows V_1 versus V_0 for the value of $(V_1^2-V_0^2)$ calculated above, while the upper curve gives the graph of V_1 versus V_0 for twice this value. The upper curve therefore indicates the range of conditions that could be associated with an upward acceleration of the houseboat equal to $-g$. This is the approximate result obtained earlier. Note that even though V_0 may vary from calm to 25 mi hr^{-1} or more, the range of V_1 possible for the given value of $(V_1^2-V_0^2)$ is no more than about 5 mi hr^{-1}. Most important, in the limiting case (lower curve, $V_0=0$), an accelerated wind-speed value over the top of the houseboat ($V+\Delta V=V_1$) of only 70 mi hr^{-1} is required to balance the houseboat's weight. These results strongly suggest that some of the wind estimates for tornadoes made from large, heavy flying objects have been too large in the past.

Even though tornadic waterspouts appear to be quite rare, the damage phenomenon at Dinner Key is not without parallel. Golden (1968) noted that two eyewitnesses to the landfall of the second, intense waterspout at Lower Matecumbe Key, Fla., claimed that a 1965 Cadillac weighing over 2 tons "was lifted a few feet off the ground and then set down again"; and what surely was a tornadic waterspout slammed into Venice, Italy, in the late evening of Sept. 4, 1970. The whirlwind killed at least 18 persons, according to an Associated Press account, when it lifted a crowded passenger motorboat from the water and sent it to the bottom of a lagoon in 30 s. The wind picked up the 25-ton boat, lifted it into the air, turned it around several times, and then plunged it back into the water.

5. THE LOWER FLORIDA KEYS WATERSPOUT PROJECT OF MAY-SEPTEMBER 1969

The five tornadoes in the Greater Miami area during 1968 and the waterspout documentation of Clemons and Rossow aroused both research and operational interest. Dr. R. H. Simpson, Director of the National Hurricane Center, NOAA, has emphasized his concern for the potential hazard that waterspouts hold for boaters in South Florida coastal waters during the summer months. Furthermore, he shares with this author the opinion that, before we can *forecast* waterspout formation, we must have *quantitative answers* to the questions listed in section 1. For these reasons, a field experimentation program was carried out during the summer of 1969 to systematically study waterspouts and their parent cumulus cloud lines in the Lower Florida Keys. The project was a joint effort of the National Hurricane Center and the NOAA-Weather Service at Key West, with headquarters at Key West International Airport. Operational plans and goals for the project were outlined by the author (1969*a*). A brief summary of data gathered during the project and some of the new documented features of waterspouts appears in Golden (1970). Of the future plans presently under review, the most promising is the erection of a twin pair of mobile Doppler radars to probe the horizontal wind field. Lhermitte's field studies (1966, 1968, 1969) in the Boulder, Colo., area indicate that the mesoscale wind field can be obtained around waterspouts and their parent cloud lines by tracking precipitation particles and chaff properly dispersed in the subcloud layer. Furthermore, smoothed vertical motions in annular rings at various elevation angles will be derived from the continuity equation.

It was felt at the outset that, if we were successful with this more tractable waterspout field program, much light would be shed on the tornado and other convective vortices and the convection that spawns them. Preliminary analyses of the 1969 waterspout data reveal this, indeed, to be the case; and detailed results will be forthcoming.

ACKNOWLEDGMENTS

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