A WSR-88D Approach to Waterspout Forecasting

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Abstract

The WSR-88D is being installed at National Weather Service (NWS) forecast and warning offices and many military installations across the county. The added capabilities of the WSR-88D over conventional radar provides the forecaster a multitude of products which allow a more complete interrogation of small scale weather features. In Florida, waterspouts and weak tornadoes account for much of the state's severe weather. They have been observed to form under certain synoptic conditions, most often during the summer and fall. Along the east-central Florida coast, waterspouts and weak tornadoes are most frequent in a relatively small area near Cape Canaveral. Observing and identifying small scale boundary interactions and the intensification of convective cells in this region using WSR-88D products from the Melbourne NWS office has proven useful in forecasting these situations.

This paper will begin by providing a brief overview of the waterspout formation process. It also offers a forecast strategy developed for the east central Florida coast using specific WSR-88D products to recognize precursor signatures to waterspout and weak tornado formation. Once a high potential for waterspout formation exists, a special statement can be issued to heighten public awareness. An example of such a statement is provided. While the techniques introduced here were designed for the east-central Florida coast, they may be applicable at other coastal offices equipped with the WSR-88D.

1. Introduction

The east-central Florida coast is affected by several waterspouts and tornadoes each year. While the majority of these events tend to be weak and short-lived; at least when compared to "classic" mesocyclone tornadoes (Schmocker et al. 1990), they still can be dangerous, and special attention must be given to prevent injury or fatality. Only through careful analysis of local geography, environmental conditions, and recognition of certain identifying features will forecasters be able to effectively warn for such events.

In this paper we will specifically address waterspouts and coastal tornadoes in the WSO Melbourne coastal warning area. We will review the process of waterspout/weak tornado formation, presenting brief case studies of recent events. WSR-88D products will be used to highlight signatures which are possible precursors to development. Finally, we introduce a forecast strategy for the Melbourne area, which may be applicable at other coastal WSR-88D sites.

2. Waterspout/Landspout Formation Processes

Numerous waterspout studies have been conducted ranging from climatology of frequencies, strengths and locations, to detailed structural analyses and formation processes (Golden 1974a, 1974b, 1977; Simpson et al. 1986). Bluestein (1985) coined the term "landspout" to differentiate between the "classic" tornado often associated with mesocyclones, and that of the non-mesocylone induced tornado. Bluestein, and Brady and Szoke (1988) have documented landspouts over the midwest and western High Plains and comment that these weak, short-lived tornadoes develop over land in a remarkably similar way to that of waterspouts. Following Bluestein's convention, we will refer to waterspouts and weak tornadoes which affect the east central Florida coast collectively as "spouts".

The principal processes of waterspout formation have been well documented (Simpson et al. 1986). It is believed that low level vortices produced along convergent boundaries become stretched in coincidence with updrafts of developing cumulus or cumulonimbus as they become vertically collocated. These surface based vortices have been observed to form along shear axes when a sea breeze interacts with the synoptic surface flow, along outflow boundaries, or in pertubated flow as a result of land/sea frictional differences such as down-wind of islands (Hess and Spillane 1990). Low level instability and lift is further enhanced when boundary interaction occurs, with spouts often developing near this intersection (Golden and Sabones 1991).

Unlike strong tornadoes associated with "classic" supercell storms, spouts form in the absence of a mesocyclone. Spouts are believed to spin-up from the surface by the stretching of a low level vortex in contrast to spin-down from mesocyclones in "classic" tornadogenesis (Wakimoto and Wilson 1989). VORTEX (Verification of the Origins of Rotation in Tornadoes EXperiment) will attempt to confirm these hypotheses in 1994-95 across the central United States (Rasmussen 1993).

Contrary to the environmental conditions most often associated with stronger tornado development, large vertical wind shear and baroclinicity are generally absent in the environment conducive to spout formation. Generally weak tropospheric winds in a quasi- barotropic environment with high humidity (mixing ratios of 15-20 g kg-1), and warm surface temperatures (25-31 deg C) are characteristics of the pre-spout environment (Hess and Spillane 1990).

Most spouts are rapidly developing and dissipating features of short duration. Golden (1973) determined the average lifetime for waterspouts in the Florida Keys to be 13 minutes. Spouts can be associated with rapidly developing cumulus which often do not have indications of precipitation or lightning. However, stronger and longer lasting spouts have been observed near or within intense convective cells. In the Florida Keys, ninety-five percent of all spouts have been observed forming along cumulus congestus cloud lines, but spouts have occasionally been observed to form beneath individual cumuli (Golden 1973).

3. East central Florida spouts

Since October 1989, WSO Melbourne has had the warning responsibility for an 80 nautical mile (nm) (149 km) stretch of the east-central Florida coast from the Volusia/Brevard County line south to the Indian River/St. Lucie County line and out to 50 nm (93 km) from shore (Fig. 1).

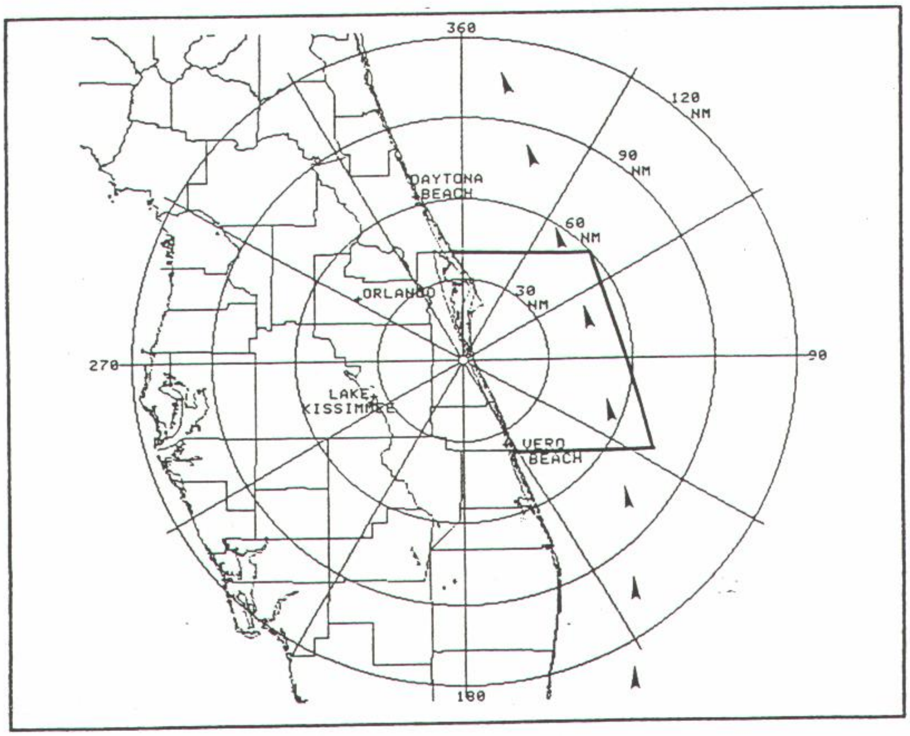

Fig. 1. Central Florida and adjacent waters. Melbourne WSR-88D at center of range rings. Arrows show approximate mean location of the center of the Gulf Stream. Bold lines indicate NWSO Melbourne coastal warning area of responsibility.

Within this area, a local maxima of spouts is observed near Cape Canaveral. Almost seventy-five percent of the near coastal spouts reported to WSO MLB come from the intracoastal lagoons or islands just west and south of Cape Canaveral and the adjacent offshore waters.

A climatological study conducted by Golden (1977) also indicated a higher frequency of waterspouts and weak coastal tornadoes near Cape Canaveral as compared with the adjacent coastal regions immediately north and south of the area. While there may be a small degree of observer bias in this data due to population clustering, it is not believed to be significant. Although the number of events in the Cape Canaveral area remain below that observed throughout the Florida Keys and portions of the Gulf Coast, damage occurs along the coast a few times per year on average.

Cape Canaveral is a discontinuity along the coast protruding several miles east of the surrounding coastline (Fig. 2).

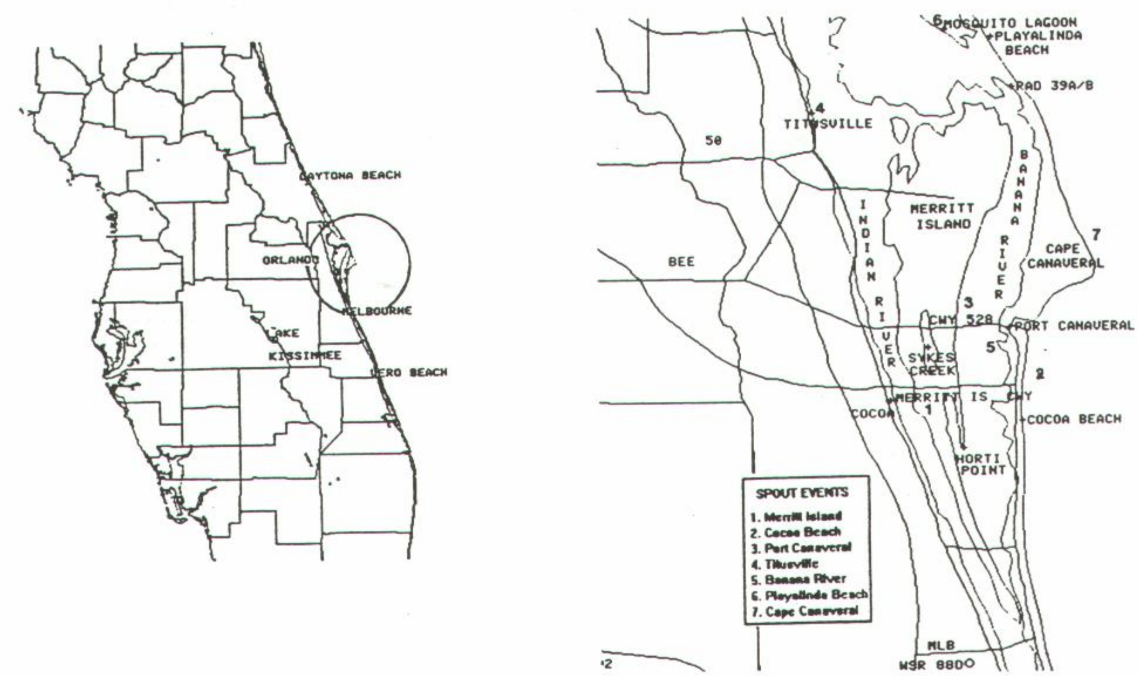

Fig. 2. Cape Canaveral area, showing location of events (1-7) described in text.

Maps and nautical charts of this area reveal that in addition to the unusual shape and orientation of the coastline, there are several intracoastal islands and large warm shallow lagoons. These geographic features produce an area of localized convergence, due to differential heating, which tends to initiate convective cells under certain synoptic regimes (Zhong and Takle 1993). This localized convergence, combined with numerous transient boundaries propagating away from thunderstorm activity over the Gulf Stream (Fig. 1) and/or the central Florida interior may account for increased spout occurrence.

With the WSO MLB WSR-88D located approximately 20 nm (37 km) south of the preferred area of spout development, real-time and post- storm analyses of these events are now possible. Until now however, even with the WSR-88D, spouts were not usually detected in real-time and continued to be largely nowcast/now-warn events based on public observation of funnel clouds or actively occurring waterspouts or tornadoes. Unfortunately, for such short-lived events this wait-and-form technique usually proved futile as the event was often over and damage, if any, had already occurred prior to the warning.

Schmocker et al. (1990) noted that the majority of spouts which have caused damage in the past were classified as F0 or F1 (Fujita 1981) in intensity and, in general, have only produced isolated cases of damage to coastal residences or watercraft. This is fortunate, considering the ever increasing number of watercraft and housing developments along the coast. The number of registered boaters in Brevard and Indian River Counties alone totaled 35,418 in year from October 1992 to September 1993.

4. Examples of Spouts

Six cases of near coastal waterspouts and one case classified as an F0 tornado have recently been observed by the MLB WSR-88D. All of these cases were located near Cape Canaveral, with five of them occurring over the Indian River, Banana River, or Mosquito Lagoon (Fig. 2). These spouts occurred during the Summer and early Fall months of June through October, when surface heating is the predominant mechanism for cell initiation. All occurred during daylight hours, between 1500 and 0100 UTC (1100 a.m. and 900 p.m. local time).

The WSR-88D creates a number of products each volume scan (every 5 or 6 minutes) from base data. These products are used in the abbreviated post-analyses presented in the next section to highlight pre-waterspout signatures. For more information about the WSR-88D and products refer to: Federal Meteorological Handbook No. 11 1991b; Crum and Alberty 1993; Klazura and Imy 1993.

a. Merritt Island Landspout

The synoptic scale pattern of 24 June 1993 was dominated by a light easterly surface flow with the Bermuda high located over the Carolinas. Winds were generally 15 knots (8 m s-1) or less from the surface through the 500 millibar (mb) level (Fig. 3a-d).

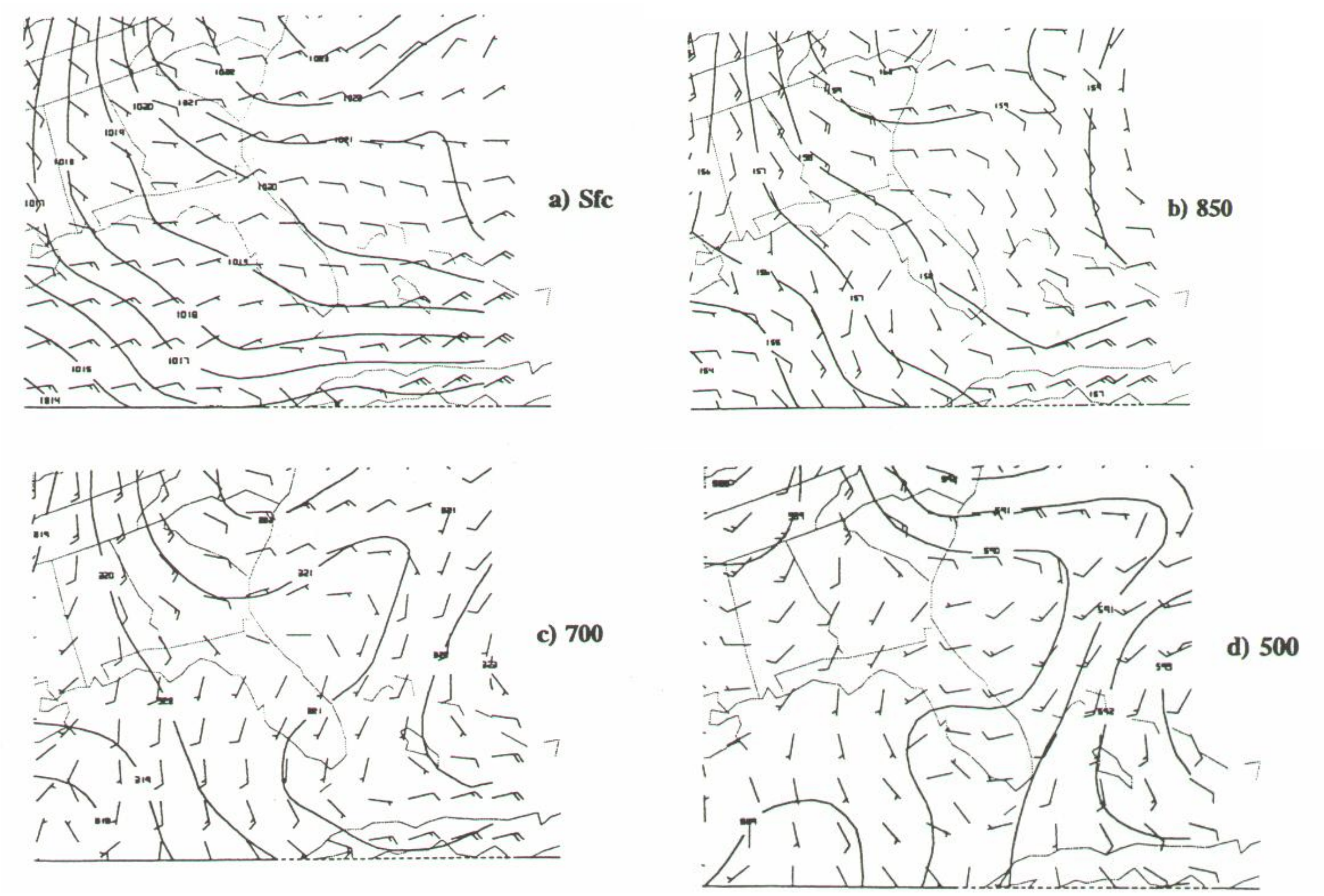

Fig 3. NGM analysis from PC-GRIDDS, 0000 UTC June 25, 1993. a) 1000 mb winds (kt) and MSL pressure (mb); b-d) wind (kt) and heights (dm) for levels indicated.

The 2200 UTC 24 June sounding from Cape Canaveral indicated a very deep moist layer with moderate instability (Fig. 4), typical for this time of year.

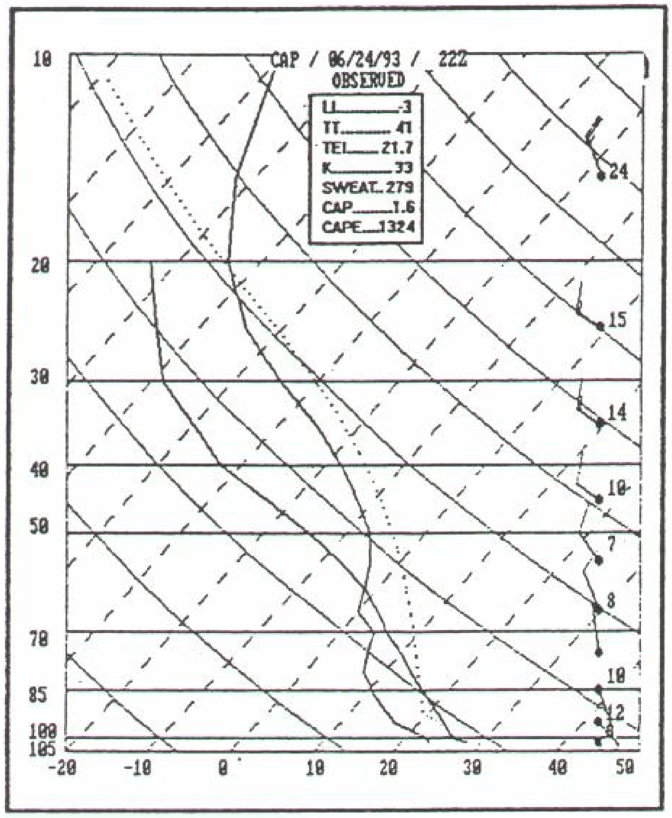

Fig. 4. Cape Canaveral Sounding at 2200 UTC, June 24, 1993.

The Melbourne WSR-88D indicated numerous thunderstorms offshore over the Atlantic, well east of Cape Canaveral throughout the late afternoon. These storms appear to have initiated a convergence line which later extended from dissipating storms northwestward toward the coast. By early evening, showers began to build along the line toward shore with the Composite Reflectivity (CR) product indicating a narrow band of moderate reflectivities (45-49 dBZ) extending from offshore to the southern edge of Cocoa Beach (Fig. A).

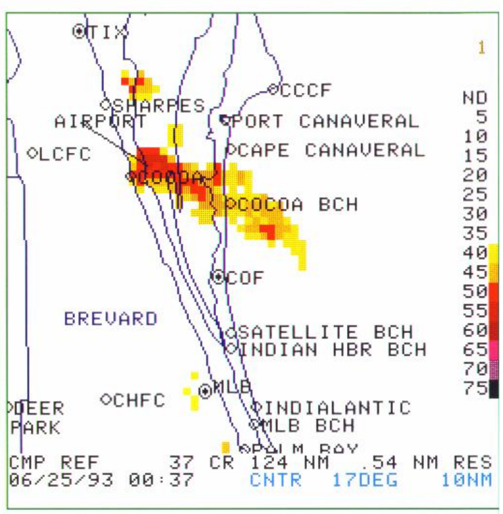

Fig. A. Composite Reflectivity, 0037 UTC, June 25, 1993.

At 0021 UTC, a stronger echo (50-54 dBZ) covered a small area just south of the Merritt Island Causeway on the east bank of the Banana River. By 0026 UTC, this echo had shifted west over the central portion of the river, and by the next volume scan (0031 UTC), the northern two-thirds of Horti Point was covered by a 50-54 dBZ echo (Fig. A). The first public report of a tornado was received around 0035 UTC. At that time the CR radar product indicated small area of 55-59 dBZ just west of Sykes Creek (Fig. 2).

The WSR-88D Echo Top (ET) and Vertically Integrated Liquid (VIL) products likewise indicated rapid cell intensification up until the time of the event (Fig. 5).

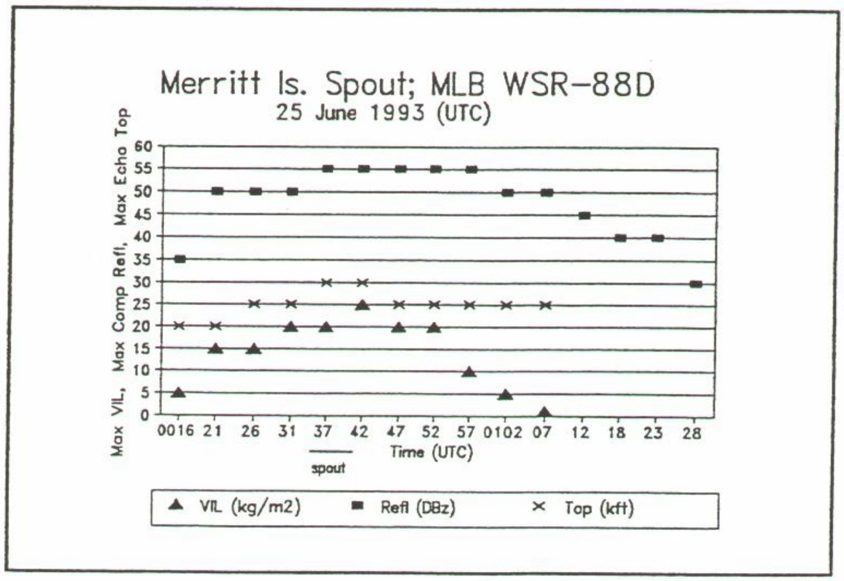

Fig. 5. Radar observed parameters for the spout cell. The estimated time and duration of the spout is indicated with a bold line below the time axis.

Both the base Velocity (V) product at 1.5 degree elevation and the Storm Relative Motion (SRM) product at 0.5 degrees revealed evidence of weak rotation for a few volume scans near the estimated time of the observed tornado. The indication was however, revealed by only a few pixels within a region of random inbound/outbound scatter. A post storm ground survey revealed that several light aircraft, a few trees, and weak structures were damaged along a short path on Merritt Island.

b. Cocoa Beach Waterspout

Weak tropospheric winds dominated the area as the Bermuda high lay over south Florida on 23 July 1993 (Fig. 6a-d).

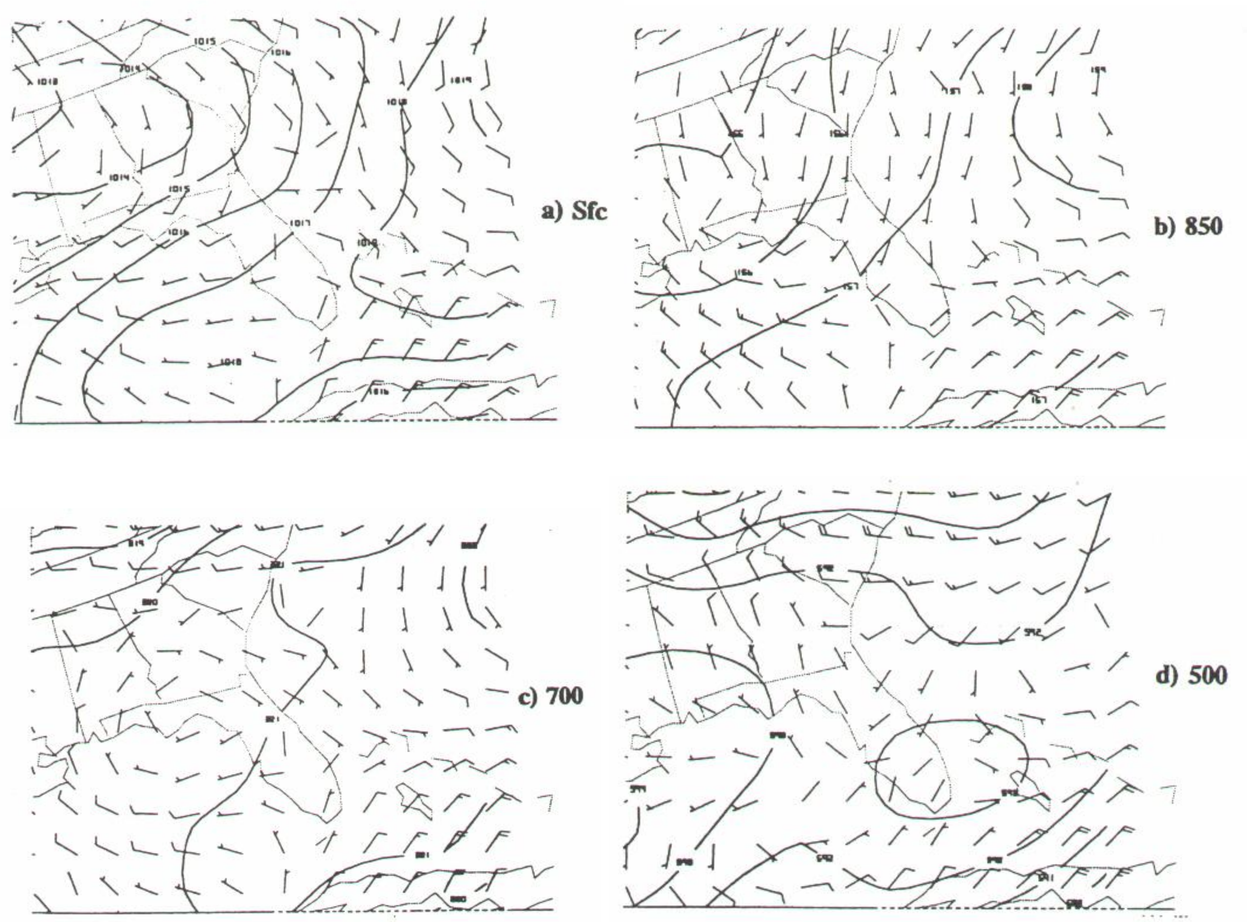

Fig. 6. Same as Fig. 3, except for 0000 UTC July 24, 1993.

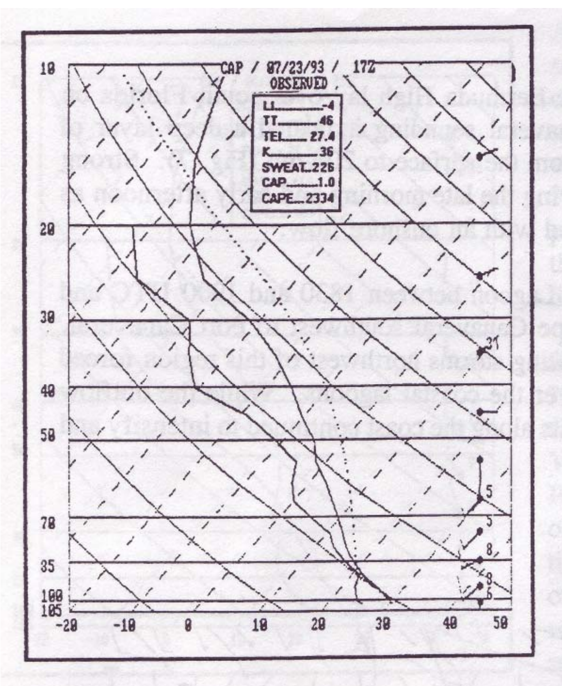

Fig. 7. Cape Canaveral sounding at 1700 UTC July 23, 1993.

The 1700 UTC Cape Canaveral sounding indicated a deep layer of moisture and light winds (<10 knots 5 ms-1) from the surface to 200 mb (Fig. 7). Strong sea breeze convergence developed near the coast during late morning and early afternoon as weak synoptic scale westerlies at the surface collided with the onshore flow.

Strong thunderstorms developed over the Mosquito Lagoon between 1830 and 1900 UTC and extended along the coast from the eastern tip of Cape Canaveral southwest to Port Canaveral. An outflow boundary propagating away from dissipating storms northwest of this region forced an area of offshore convection, and initiated cells over the coastal lagoons. While the outflow boundary propagated toward the sea breeze front, cells along the coast continued to intensify and build southward (Fig. B).

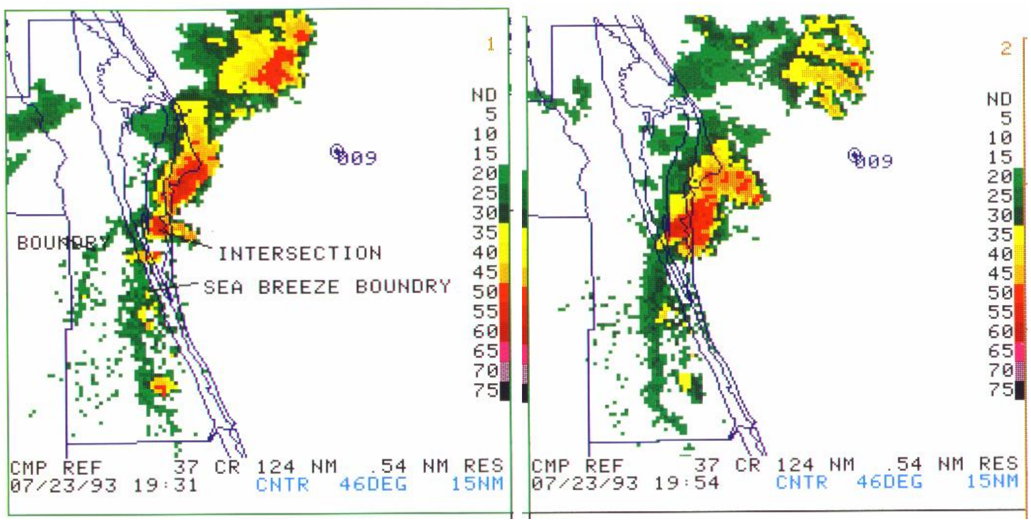

Fig. B. Composite Reflectivity 1931 and 1954 UTC, July 23, 1993.

At 1930 UTC, a large waterspout was reported just offshore Port Canaveral. By that time, WSR-88D radar products indicated the rapid intensification trend of the spout- producing cell had ceased. VIL, ET, and CR products indicated the cell maintained nearly steady-state conditions over the next 30 minutes (Fig. 8).

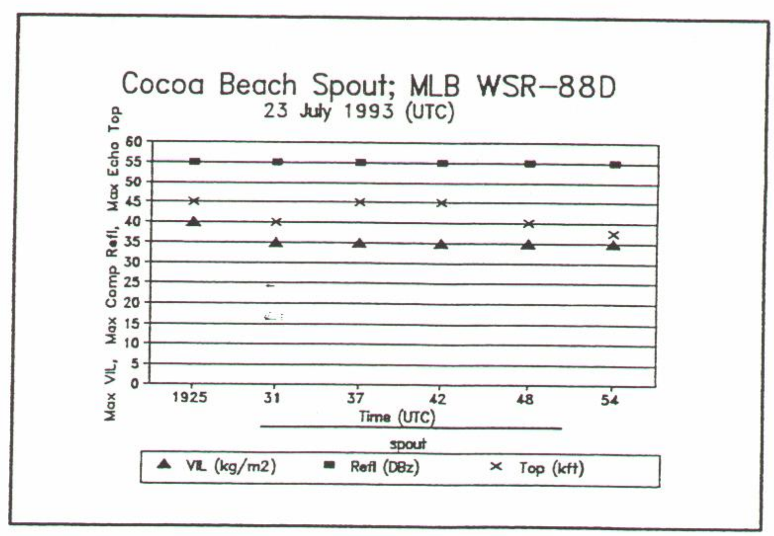

Fig. 8. Radar observed parameters for the spout cell. The estimated time and duration of the spout is indicated with a bold line below the time axis.

Numerous reports indicated the persistence of the large spout as it moved south to the Cocoa Beach coastal waters and dissipated just prior to 2000 UTC. Although there were no indications of rotation with this cell in any of the velocity products, a small area of winds of 26-35 knots (13-19 m s-1) were detected in the 0.5 degree 0.54 nm (1 km) V product. The waterspout remained offshore during its lifetime and did not produce any damage to coastal structures or vessels.

c. Port Canaveral Waterspout

Weak easterly surface flow with mid-level ridging across north Florida characterized the synoptic pattern on 10 August 1993 (Fig. 9a-d). A 500 mb trough off the northeast Florida coast advected slightly cooler mid-level temperatures into the northern half of Florida, likely providing additional instability to the moist tropical airmass already in place (Fig. 10).

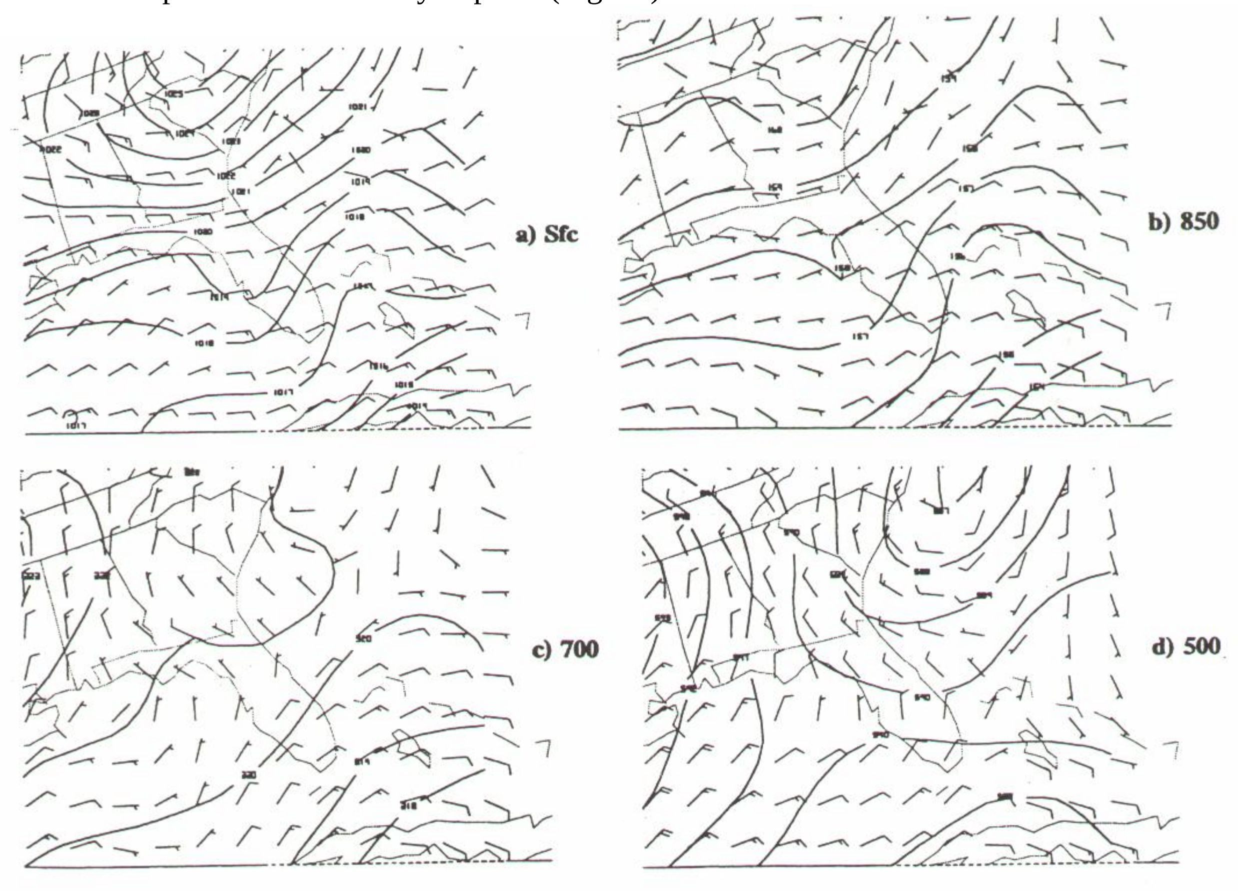

Fig 9. Same as Fig 3, except for 1200 UTC August 10, 1993.

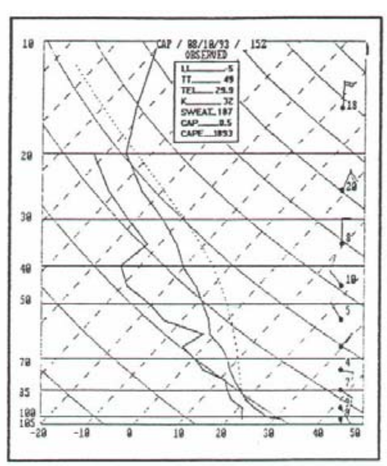

Fig. 10. Cape Canaveral sounding at 1500 UTC August 1993.

At 1704 UTC, there was no indication of radar-detectable boundaries or precipitation echoes across the lagoon area south and west of Cape Canaveral. By 1718 UTC, a moderately strong (55-59 dBZ) CR echo had rapidly developed just west of the Port Canaveral and continued to intensify through the next several volume scans (Fig. C). At 1730 UTC, reports indicated that a waterspout was associated with this isolated cell. VIL, ET, and CR products confirmed the steady, rapid intensification of the cell prior to spout formation (Fig. 11).

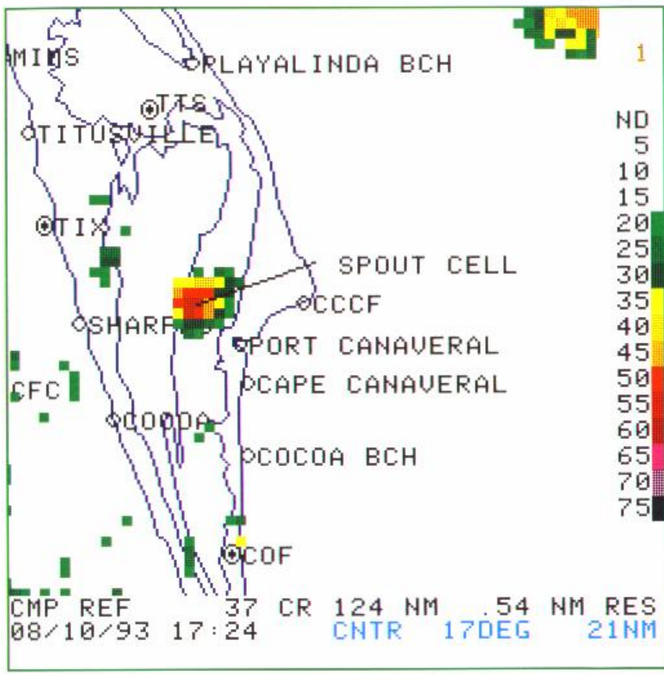

Fig. C. Composite Reflectivity 1724 UTC, August 10, 1993.

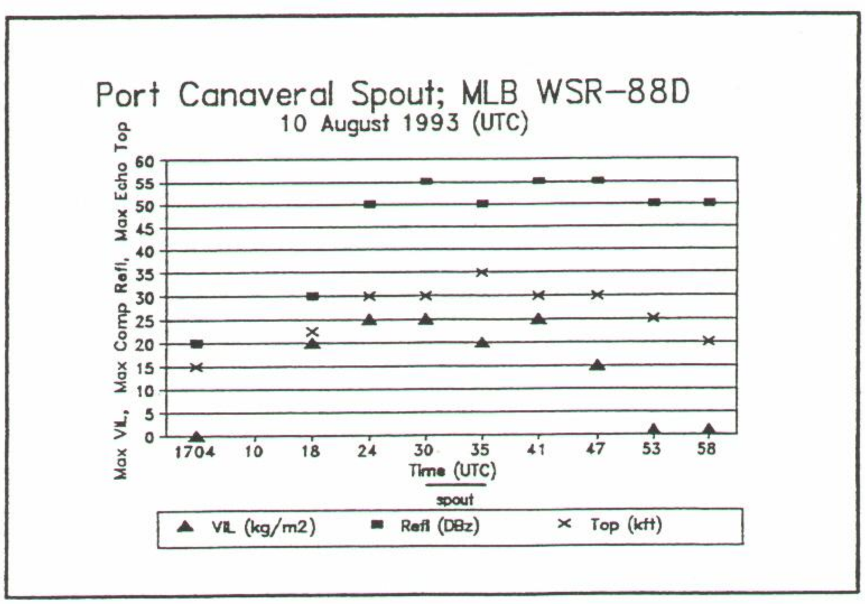

Fig. 11. Radar observed parameters for the spout cell. The estimated time and duration of the spout is indicated with a bold line below the time axis.

Convection was occurring over the central Florida interior and well offshore. Analyses of all available radar data indicated the cell remained isolated throughout its lifetime and apparently did not initiate from, or interact with, any boundaries. The cell also lacked radar-observed rotational characteristics and enhanced low- level wind fields. The waterspout remained offshore during its lifetime and did not cause any reported damage.

d. Titusville Waterspout

The synoptic pattern on 25 August 1993 consisted of a weak vertically stacked low over the central Gulf of Mexico with a inverted trough extending northeastward across central Florida. A light east to southeast flow was observed at low and mid levels across the Florida peninsula (Fig. 12). The morning Cape Canaveral sounding revealed abundant moisture below 600 mb and moderate instability (Fig. 13).

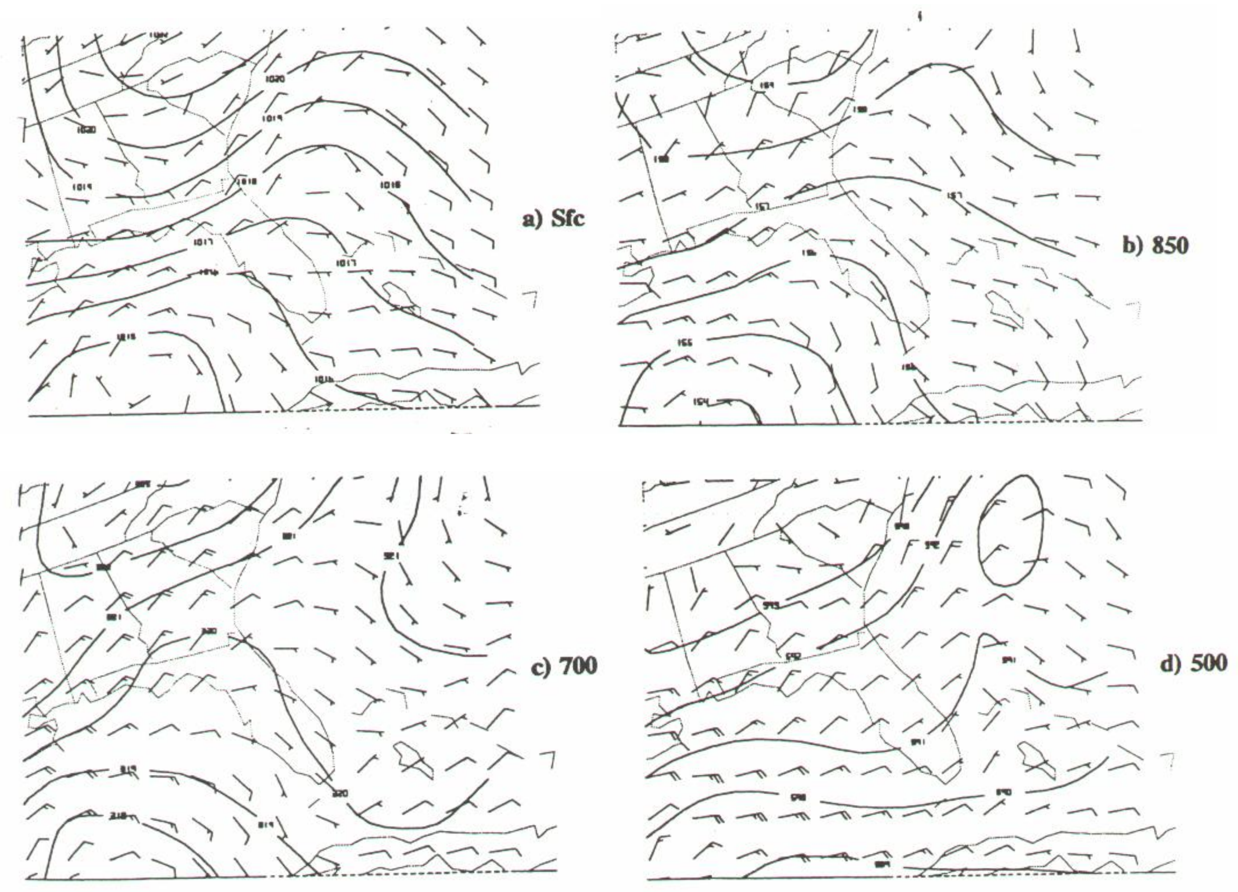

Fig. 12. Same as Fig. 3, except for 1200 UTC August 25, 1993.

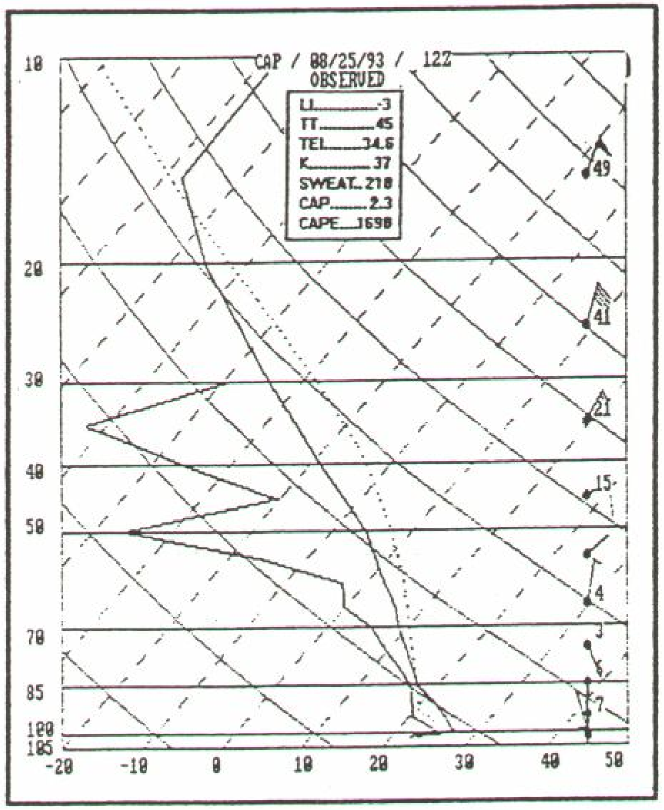

Fig. 13. Cape Canaveral sounding
at 1200 UTC August 25, 1993.

At 1439 UTC, radar indicated a small area of moderately strong (45- 49 dBZ) echoes 7 nm (13 km) east of Titusville. The cell increased to 50-54 dBZ by the next volume scan, and then began to dissipate by 1451 UTC. At this same time, another cell developed just north of Titusville over the Indian River. Both cells appear to have developed in response to a boundary stretching from the Atlantic well offshore of Cape Canaveral, southwestward across the intracoastal waters. This boundary may have been initiated by a cluster of thunderstorms offshore of Cape Canaveral.

The new cell continued to intensify and displayed 50-54 dBZ reflectivities by 1503 UTC (Fig. D). The following scans indicated the cell contained a 55-59 dBZ core. A waterspout was reported with this cell at 1515 UTC. VIL, ET and CR products all indicated maximum values at or just prior to the time of waterspout formation (Fig. 14). While the spout was occurring, weak rotation was apparent within a few pixels in the 0.54 nm (1 km) resolution V product at the 1.5 degree elevation angle.

The strong cell drifted west with the spout persisting for approximately 5 minutes before moving onshore at Titusville and dissipating. Newspaper reports indicated that minor wind damage occurred to a few coastal businesses and several automobile windows were damaged.

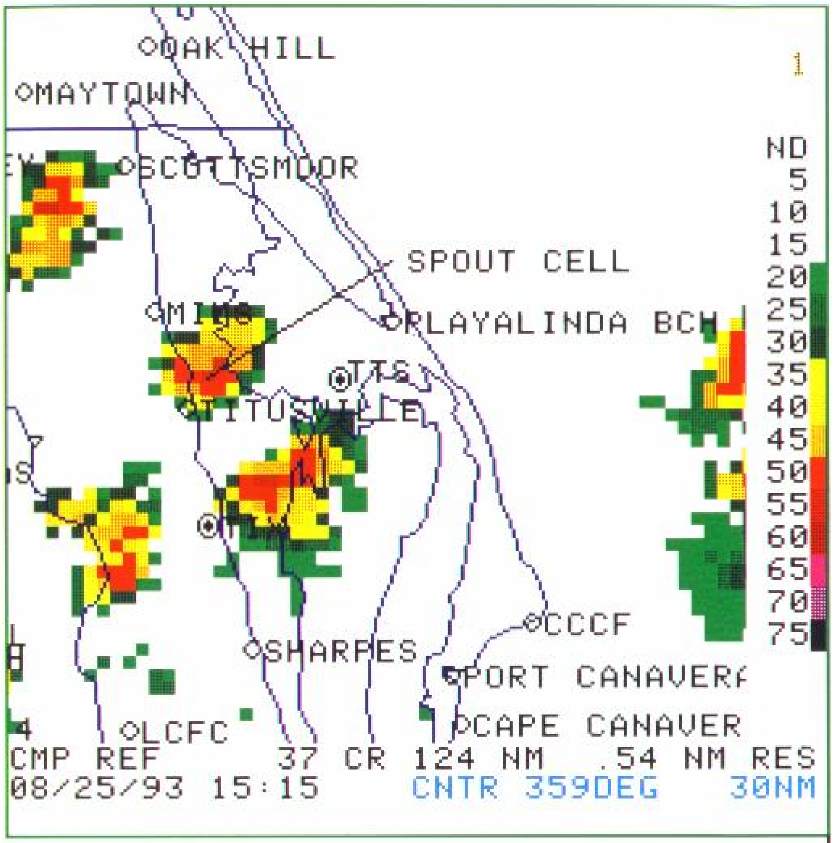

Fig. D. Composite Reflectivity 1515 UTC, August 25, 1993.

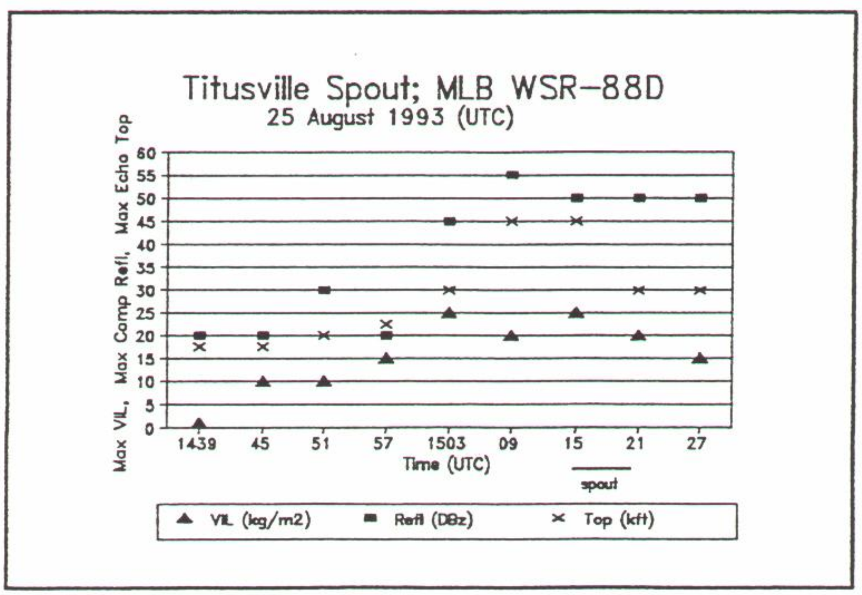

Fig. 14. Radar observed parameters for the spout cell. The estimated time and duration of the spout is indicated with a bold line below the time axis.

e. Banana River Waterspout

Synoptic scale conditions during 27 September 1993 indicated the presence of a deep layer ridge axis across the Florida straits and Bahamas (Fig. 15a-d). A weakening frontal boundary had dropped into Alabama and Georgia and was approaching north Florida. During the early afternoon, strong pre-frontal convection commenced over the north-central and central Florida peninsula. The 1500 UTC sounding from Cape Canaveral revealed a generally moist airmass from the surface to 300 mb with a unidirectional south southwest wind flow (Fig. 16). Winds steadily increased from 10 knots (5 m s-1) at the surface to 35 knots (18 m s-1) at 300 mb. An easterly sea breeze of around 10 knots became well established by mid-afternoon along the coast.

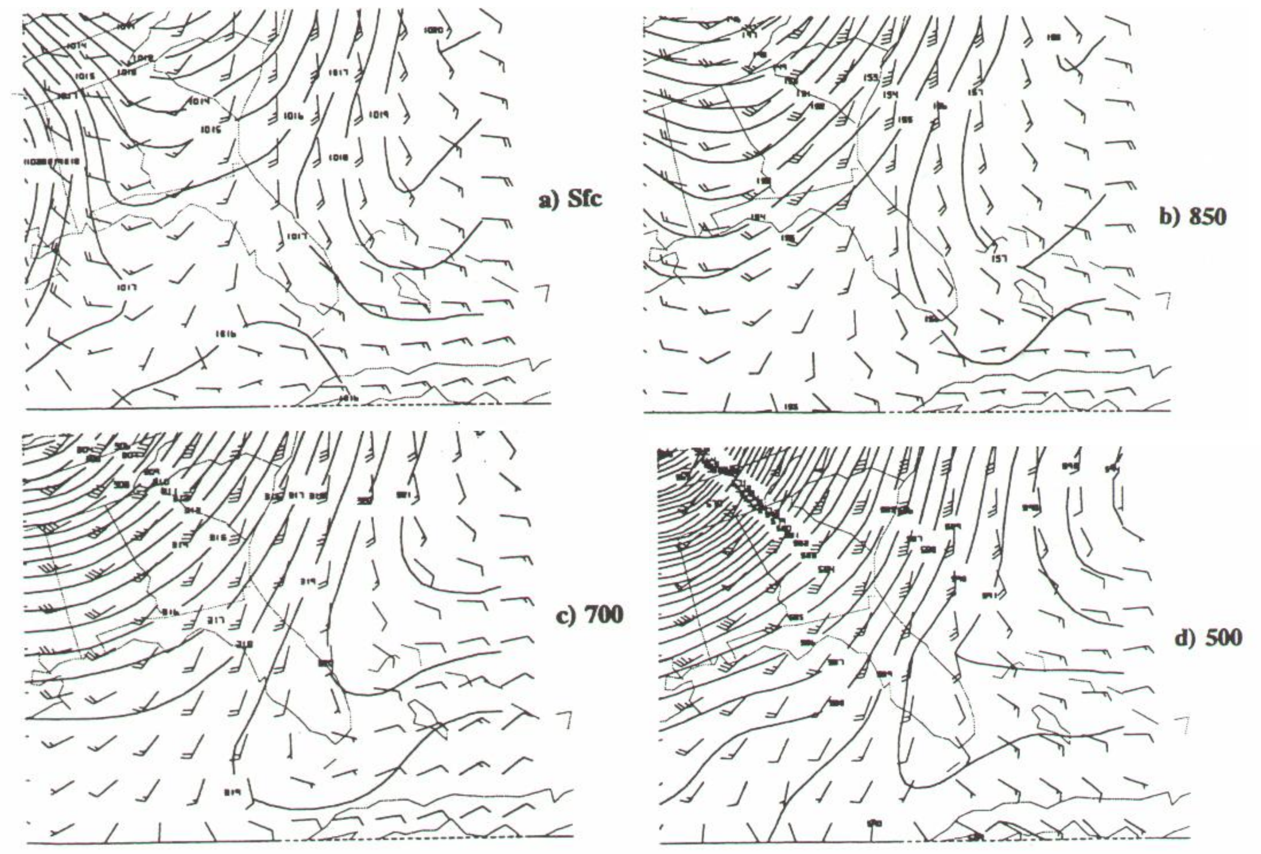

Fig. 15. Same as Fig 3, except for 1200 UTC September 27, 1993.

At 1913 UTC, radar indicated strong thunderstorms forming over the central Florida interior and adjacent coastal waters, with thunderstorm activity over the coast in the southern portion of the Banana River. By 1937 UTC, the sea breeze boundary (denoted by "1" in Fig. E) was detected in the CR product by a line of less than 20 dBZ echoes extending from Vero Beach, north over Merritt Island, to just west of Port Canaveral. Two additional boundaries (indicated as "2" and "3" in Fig. E) were detected west of the sea breeze front and were moving southwest toward the coast. At this time, boundary "2" which extended from Lake Kissimmee to Cocoa, was only 5 nm (9 km) west of boundary "1". The 2002 UTC volume scan indicated boundary "2" had begun to intersect the sea breeze front, from just northeast of Cocoa to 2 nm (4 km) north of Horti Point.

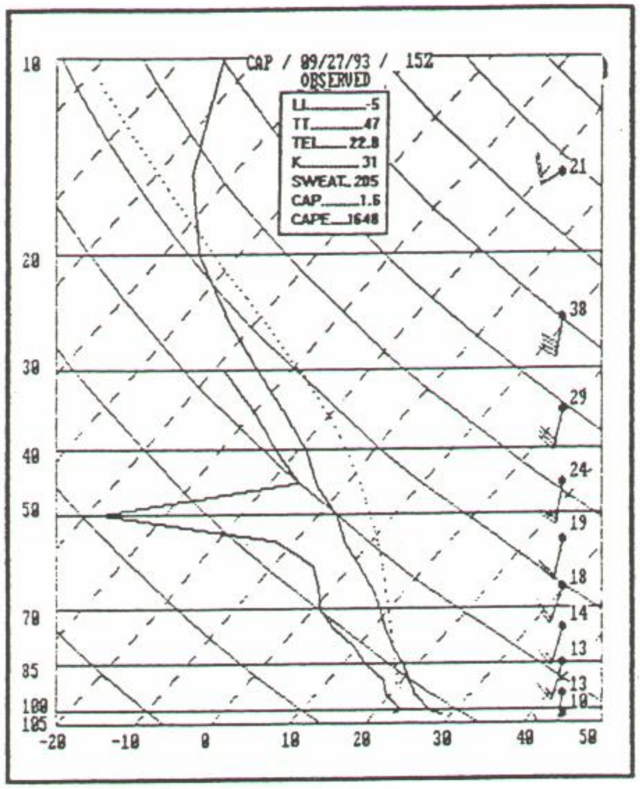

Fig. 16. Cape Canaveral sounding at
1500 UTC September 27, 1993.

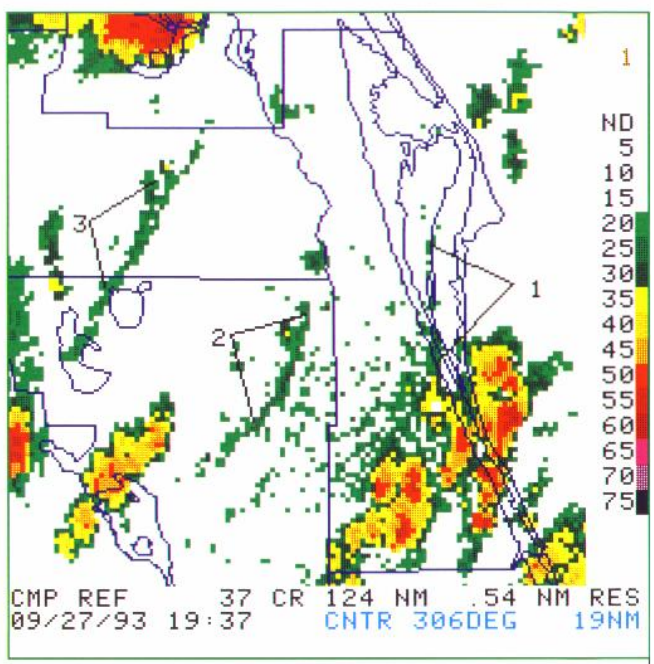

Fig. E. Composite Reflectivity 1937 UTC, September 27, 1993.

Within 15 minutes, the first convective cell developed over Cocoa and by 2027 UTC a second cell was developing over Port Canaveral. By the next volume scan at 2032 UTC, the area from Port Canaveral to Cocoa exploded with strong convective cells which eventually formed into a solid line and stretched from just offshore of Playalinda Beach to 6 nm (11 km) west of Melbourne by 2038 UTC. The rapid intensification of the cell is shown in Fig. 17 with the low- level R, CR, VIL, and ET products all increasing rapidly prior to, and during the initial stages of spout development.

Public reports indicated that a waterspout developed over the Banana River about one-half mile south of the 528 Causeway (CWY) at 2030 UTC. Numerous waterspout reports were received during the next half-hour as the spout traversed northward over the west basin of Port Canaveral and moved to a position over the north Banana River before dissipating around 2110 UTC. No reports of damage were received.

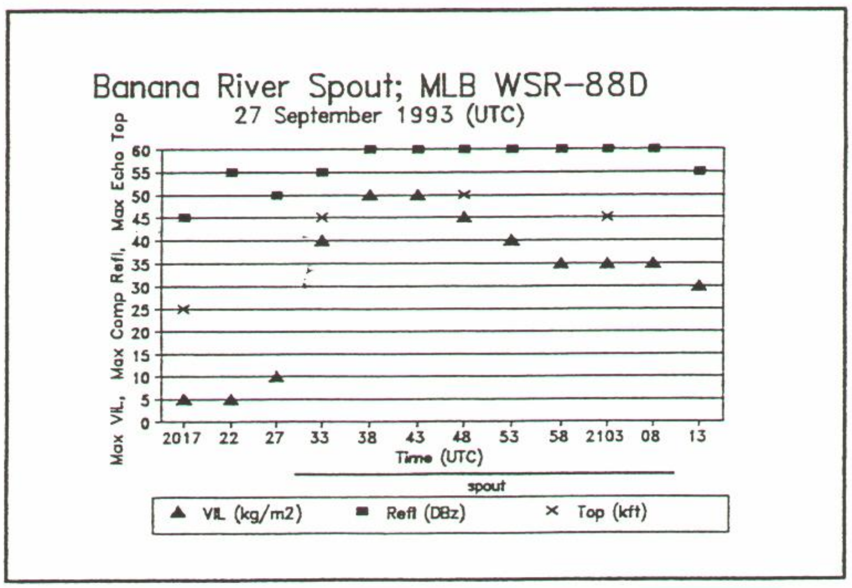

Fig. 17. Radar observed parameters of the spout cell. The estimated time and duration of the spout is indicated with a bold line below the time axis.

f. Playalinda Waterspout

Within 24 hours of the Banana River waterspout (previous case), another spout event occurred. By 1200 UTC on 28 September 1993 (Fig. 18a-d), surface winds backed to a northeasterly direction in response to a cold front moving over the area. Winds above 850 mb remained west to southwest but weakened from the previous day (Fig. 15). The 1500 UTC Cape Canaveral sounding continued to indicate that the airmass over the area was extremely moist and unstable (Fig. 19).

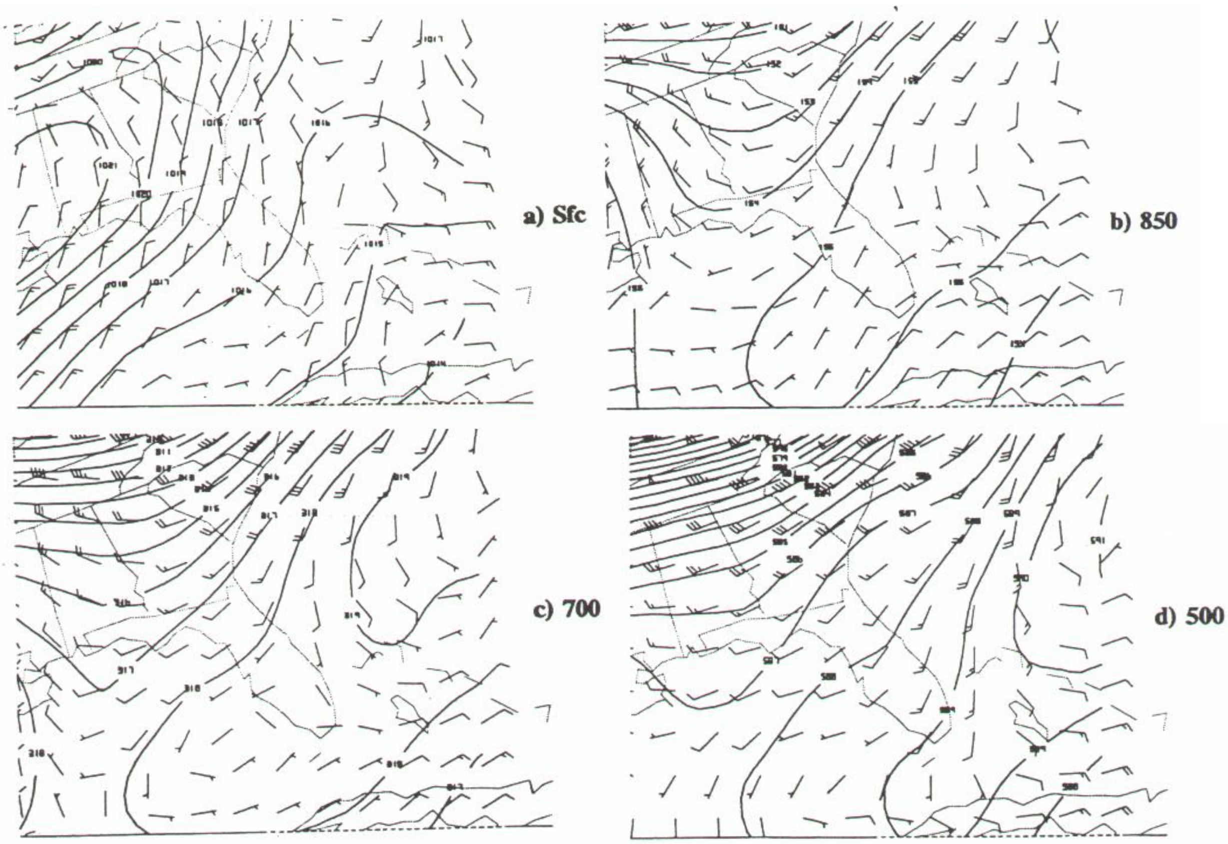

Fig. 18. Same as Fig 3, except for 1200 UTC September 28 1993.

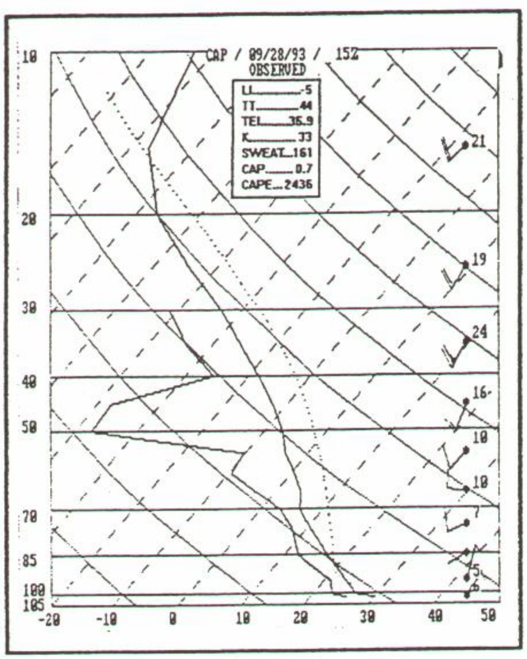

Fig. 19. Cape Canaveral sounding at 1500 UTC September 28, 1993.

Mid-morning satellite imagery indicated a northeast-to-southwest orientated cumulus cloud line with embedded convective cells over the Gulf Stream from 30 nm (56 km) east of Daytona Beach to just north of Playalinda Beach. Throughout the morning, weak radar echoes below 20 dBZ were largely masked by an extensive area of Anomalous Propagation (AP) surrounding the radar site. The AP was indicative of the highly stable and moist morning atmosphere beneath the nocturnally induced radiation inversion.

By late morning, after filtering out low reflectivity values, a few pixels of 25 dBZ CR echo were detected, extending from an area of offshore convective activity to the coast 3 nm (6 km) north of Playalinda Beach (Fig. F1).

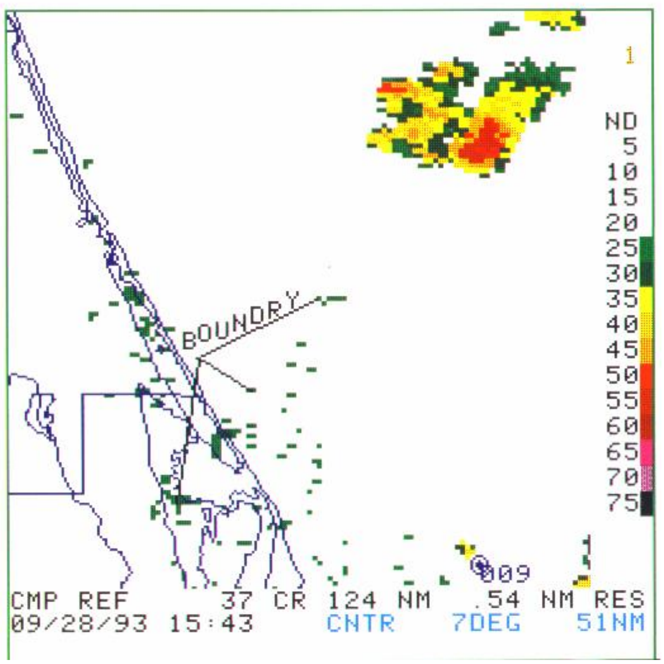

Fig. F1. Composite Reflectivity 1543 UTC, September 28, 1993.

These echoes appeared to be associated with a weak low-level boundary. At 1549 UTC, a scattered area of 20-25 dBZ was indicated from Titusville to 15 nm (28 km) east of Playalinda Beach. By the next volume scan (1555 UTC), a small echo over the Mosquito Lagoon, 2 nm (4 km) north of Playalinda Beach had rapidly increased to an area of 45-50 dbZ (arrow, Fig. F2). A brief waterspout, as described by public reports, occurred with this cell beginning around 1558 UTC. The short-lived cell quickly weakened to 30 dBZ by 1601 UTC and completely dissipated by the following volume scan (1607 UTC).

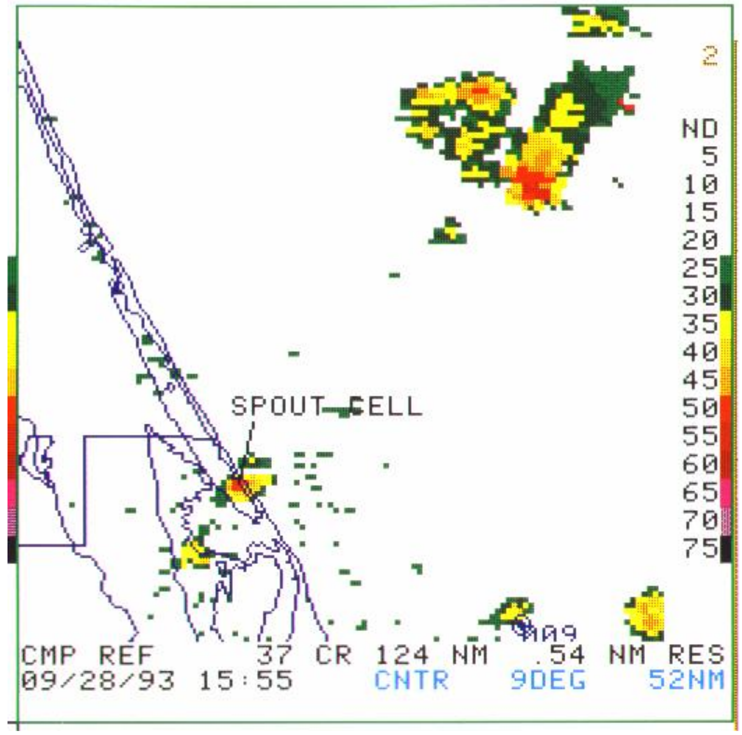

Fig. F2. Composite Reflectivity 1555 UTC, September 28, 1993.

VIL, ET, and CR products all peaked prior to waterspout generation, and showed a steady decreasing trend once the spout dissipated (Fig. 20). There were no reports of damage with this spout.

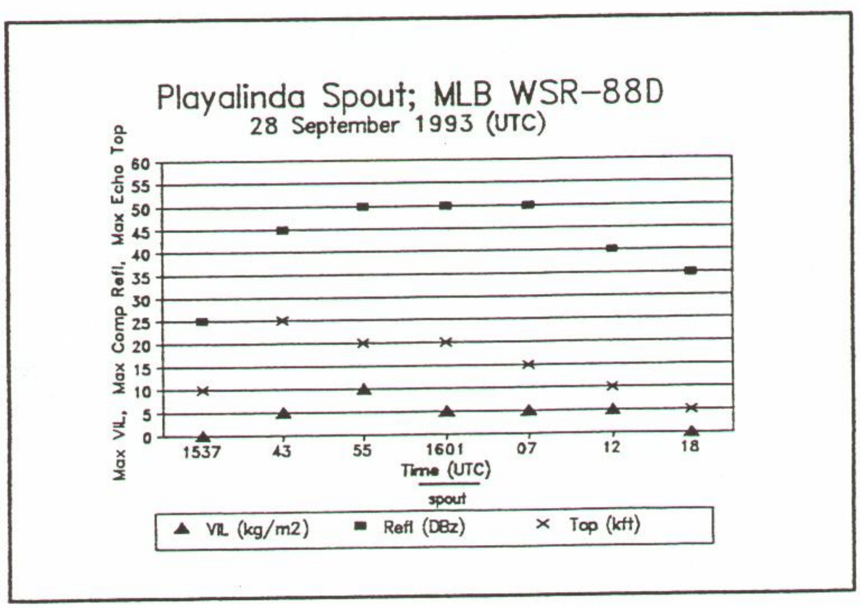

Fig. 20. Radar observed parameters of the spout cell. The estimated time and duration of the spout is indicated with a bold line below the time axis.

g. North Cape Canaveral Waterspout

The synoptic conditions on October 22, 1993, were similar to the previous two events. A weak front was positioned over north Florida with prefrontal conditions dominating the area over central Florida and the adjacent coastal waters (Fig. 21a-d). The Cape Canaveral sounding indicated the airmass over the area was extremely moist and unstable at 1500 UTC (Fig. 22).

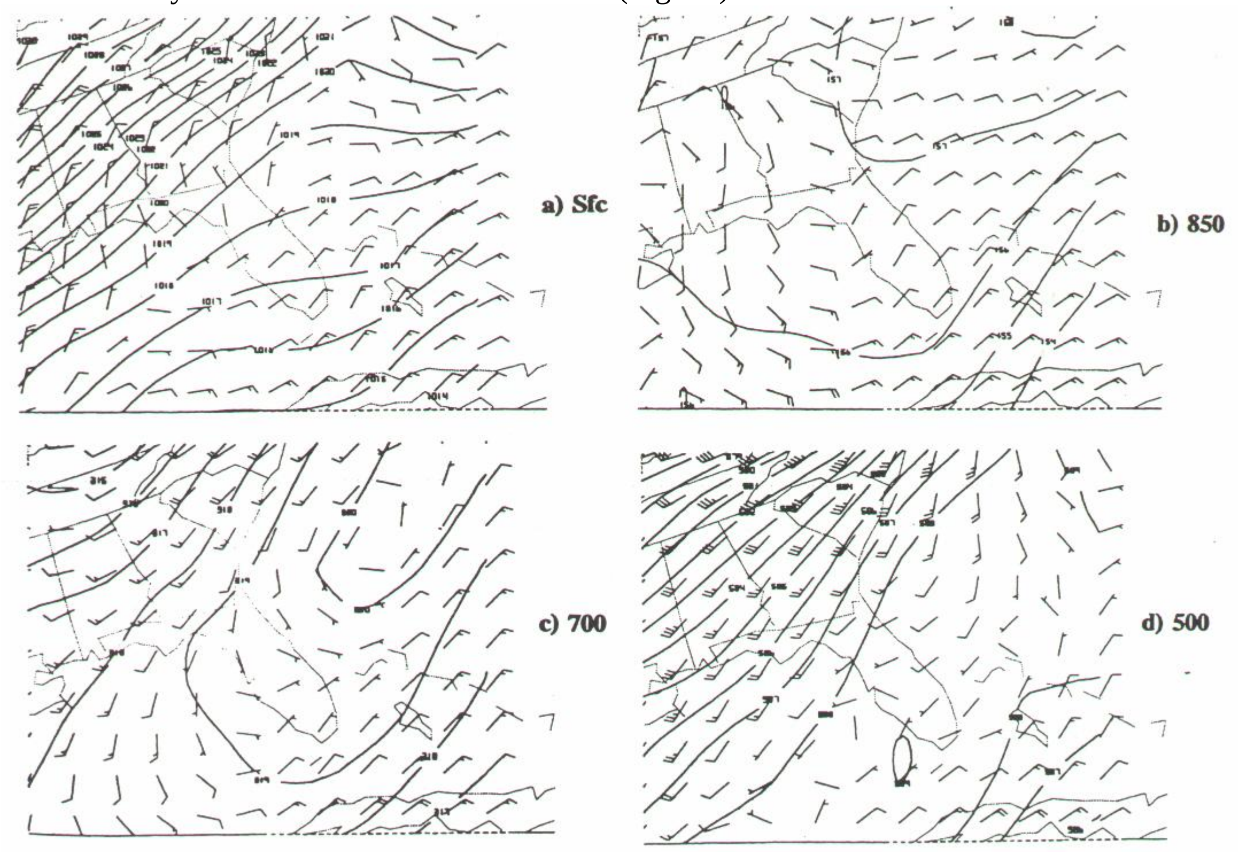

Fig. 21. Same as Fig. 3, except for 1200 UTC October 22, 1993.

During the morning hours, showers and thunderstorms were occurring over the Gulf Stream about 50 nm (93 km) east of Daytona Beach and Cape Canaveral - a continuation from activity the night before. A persistent stationary boundary, indicated by a line of cumulus congestus, was evident in the visible satellite imagery and the lowest elevation R and CR products. This boundary extended from the area of showers and thunderstorms offshore over the Gulf Stream southwestward to Cape Canaveral.

Convection also began to develop over central Florida as surface temperatures climbed into the mid 80's over much of the area. By 1542 UTC showers had begun to develop inland along the southwestern edge of the boundary and an initial cell formed offshore, just east of Cape Canaveral (Fig. G1). By 1548 UTC, the CR product indicated 50-54 dBZ reflectivities in this cell. A SKYWARN observer reported a waterspout offshore just east of Cape Canaveral commencing around 1552 UTC. The spout was also reported by observers at the Kennedy Space Center soon thereafter.

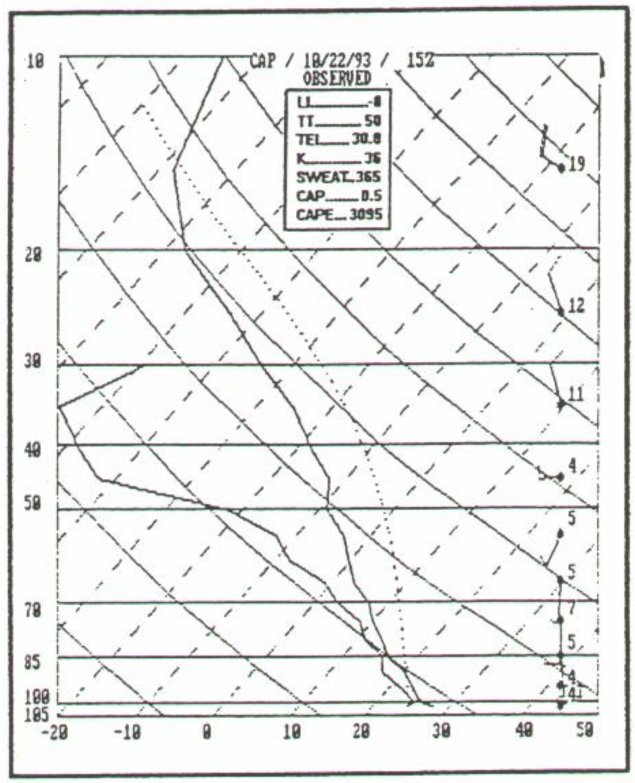

Fig. 22. Cape Canaveral sounding at 1500 UTC October 22, 1993.

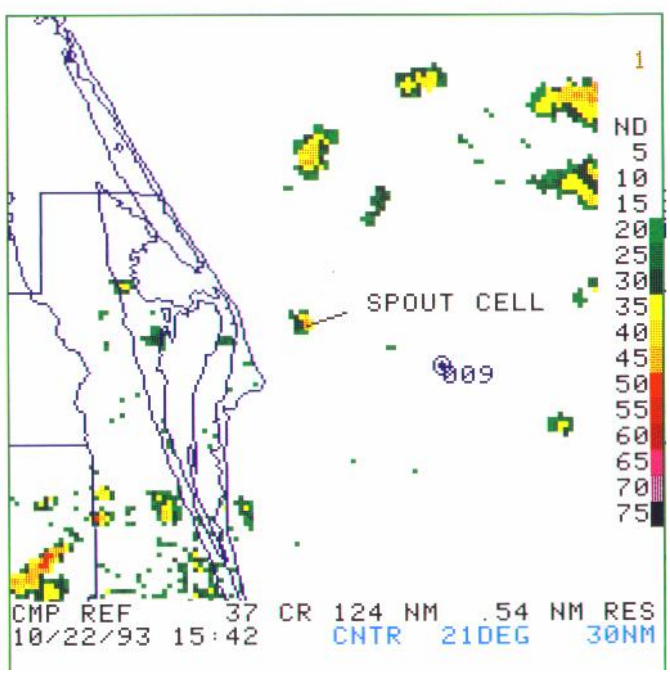

Fig. G1. Composite Reflectivity 1542 UTC, October 22, 1993.

The volume scan at 1600 UTC (Fig. G2) indicated that CR values continued in the 50-54 dBZ range, decreasing to 45-49 dBZ by 1606 UTC. The spout producing cell maintained its intensity briefly before rapidly dissipating, which was apparent in the tendencies of the ET, VIL, and CR values (Fig. 23). This brief spout did not threaten the coast or cause damage to vessels.

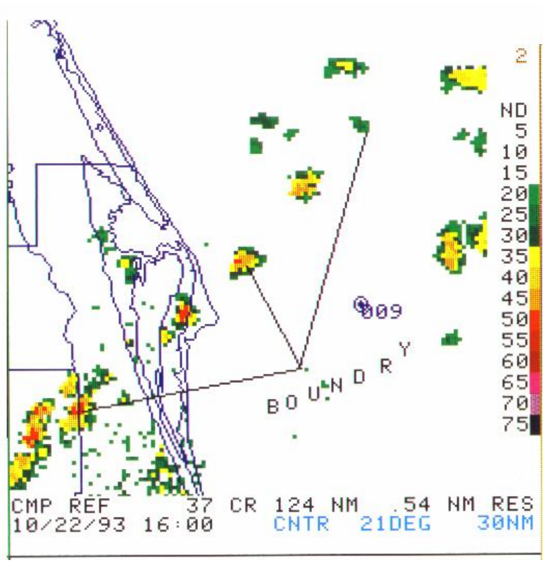

Fig. G1. Composite Reflectivity 1600 UTC, October 22, 1993.

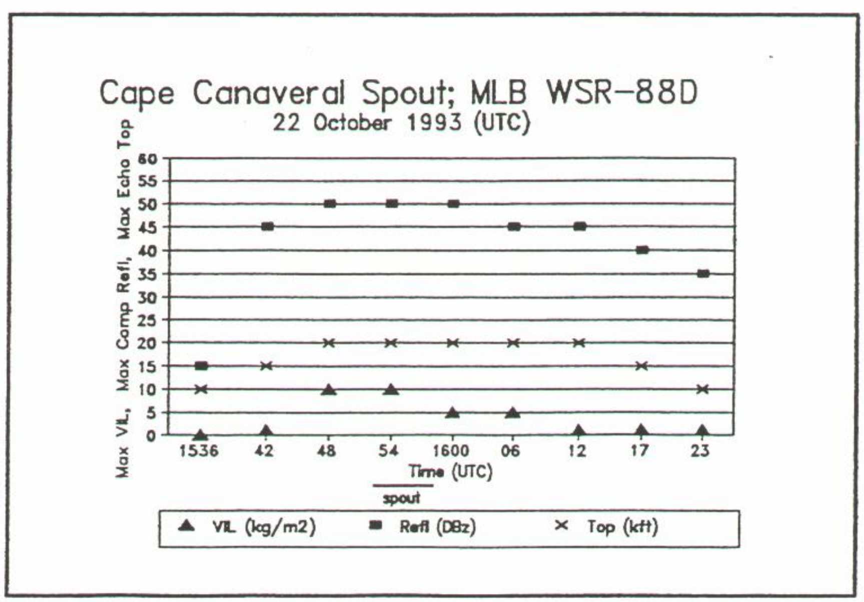

Fig. 23. Radar observed parameters of the spout cell. Bold line at bottom represents the estimated spout duration.

5. Event Synopsis

Six of the seven spouts occurred under weak tropospheric winds. The remaining case, the Banana River spout, occurred under a slightly stronger flow, with winds in the 10 to 20 knot range from the surface to 500 mb. Deep moisture was present for all cases and surface flow along the coast was east to southeast during five of the events. During the other two events, the synoptic surface flow was south to southwest with a northeast to east sea breeze flow along the coast. All spouts occurred with cell development in the Cape Canaveral area as the cells were rapidly developing.

In four of the cases, distant convective activity appears to have initiated low-level boundaries near or along which the spout- producing cells later developed. It was apparent only in the Cocoa Beach and Banana River waterspouts that two boundaries actually intersected. However, for the Merritt Island landspout case there were several boundaries indicated by radar near the area and these may have influenced spout formation. The time between initial cell detection and the first report of a spout sighting was around 25 minutes for each case.

After careful review of the WSR-88D archived products, weak rotation was noticed near the 2500 ft (758 m) level for two of the seven cases. The rotation was less than 30 knots (15 m s-1) storm relative, over a small area, and was observed only for a few volume scans during each event. This rotation was only apparent in the 0.54 nm (1 km) resolution 1.5 degree V and SRM products. A small area of radial winds in the 26 to 35 knots (13 to 18 m s-1) range was indicated in the 0.5 and 1.5 degree elevation V and SRM products for the Cocoa Beach, Banana River, and Cape Canaveral waterspouts, but no rotation was apparent.

The VIL, ET, and CR products all showed steady increasing trends prior to spout formation, indicative of rapid cell development. The spouts were first observed around the time of maximum VIL, ET, and CR values and dissipated as parent storms weakened. Each of the observed cells increased to reflectivities around 55 dBZ with moderate VIL values, and generally possessed low tops as compared to convective cells over land. These values are not unusually large when compared with other storms across east central Florida; rather, it appears the trend in intensity is a significant factor.

Paxton and Shepherd (1993) proposed the development of WSR-88D algorithms tailored to severe weather detection for central Florida. Digitized WSR-57 data (RADAP) used in their study suggested that positive VIL growth rates of 20 kg m-2 or greater in a ten minute period, or a positive echo top height increase of 15,000 feet (4550 m) or more within 10 minutes frequently led to severe weather. Data from the present study confirms that a VIL and ET growth algorithm would be helpful in delineating potential spout events. Two of the seven spouts analyzed by the MLB WSR-88D exceeded the Paxton and Shepherd thresholds. Both of these cases involved relatively long-lived waterspouts. The remaining cases approached the VIL and ET severe weather criteria.

Additional research using a larger data set is needed to further evaluate the prospects for such an algorithm. Forecasters at the Melbourne and Tampa Bay WSO's are planning to examine this topic in more detail during future years.

6. Forecast strategy

A systematic approach to coastal spout forecasting is needed to increase the forecasters awareness of development potential and to convey this information to the public prior to occurrence.

1) The initial strategy is to determine whether the synoptic conditions are favorable for spout development since they are contrary to the environment for strong tornadoes. The latest sounding should indicate moisture through a deep layer from the surface to around 500 mb and a weak tropospheric wind field, favoring an onshore flow at low-levels.

2) Once the synoptic scale environment is determined to be in place, detecting the presence and movement of boundaries and rapid cell intensification becomes very useful in determining the potential for spout formation. The WSR-88D "Combine Up" function is useful in highlighting boundaries in the CR and lowest elevation R products. This function can be used alone, or in conjunction with filtering the lowest one or two reflectivity levels to better enhance boundaries.

3) Rapid cell development can be detected by an increasing trend in the ET, VIL and CR products. Noticing this development over the preferred spout area, especially along or near boundaries and intersections, can be important when trying to predict the location and occurrence of spouts. Although these radar products are highlighted, a number of other radar products - for example, Reflectivity Cross Sections and base R for various elevation angles - are also useful in detecting development in cells. Satellite imagery and surface observations can also confirm radar characteristics.

4) Once conditions suggest a high potential of spout formation,the WSR-88D Routine Product Set (RPS) list should be updated (or a special spout RPS list should be implemented) to include some high resolution products. In addition to developing a spout RPS list, user functions (macros) can be created in advance to display high resolution four-panels of the lowest elevation angle V and SRM products. The 0.13 nm (0.25 km) V and SRM products at elevation angles which will bisect developing cells generally below 4000 feet should be most useful in tracking the location of spouts (or more likely an area of strong winds) after initial development.

Rotational characteristics of spouts typically are about an order of magnitude smaller than the highest resolution radar product available, therefore, associated cyclonic signatures are usually unresolvable. Also, since rotation is most prevalent at very low levels within the parent cell, it is unlikely that velocity analyses beyond about 30 nm (56 km) of the radar site will be helpful. However, the base Spectrum Width (SW) product may prove useful to highlight or confirm spout presence through the indication of isolated strong turbulence and should be included on the spout RPS list. While the VIL and ET products seem to perform well as storm intensification indicators, spout-producing cells often are not the strongest cells as indicated by radar. Subtle increases of CR, ET and VIL values combined with areas of localized convergence and approaching boundaries remain the key identifying factors.
Response time during a spout is paramount. When a spout develops, radar products from the lowest elevation scans must be interrogated closely. If possible, a Volume Coverage Pattern (VCP) RESTART command should be considered (at the Unit Control Position, UCP) after the 2.4 or 3.4 deg scan to allow

for immediate re-evaluation of the lowest level products.

For warning purposes, the NWS does not differentiate between spouts and strong tornadoes, since even weak spouts have some potential for serious injury, if not death. A tornado warning is required if a tornado is sighted, indicated by radar, or if a waterspout threatens the coast. For non-threatening waterspouts well offshore, a Special Marine Warning is normally sufficient to cover the event. For coastal spouts, however, tornado warnings frequently are issued after the initiation of the event once public reports are received. Many times the spout has dissipated by the time the warning is heard by the public, and therefore only adds confusion to the situation.
For the benefit of coastal residents and mariners, it would be useful to heighten awareness ahead of a potential spout event, at least under certain conditions. Suggested conditions are:

1) When certain synoptic patterns occur which are indicative, or supportive of spout formation.

2) When a developing line of convection is approaching or forms over the area and nearby boundaries are detected.

3) When rapid initiation of isolated convection is occurring over an area which has been determined to be prone to spout formation.

To alert the public in advance to the possibility of spout formation, a Marine Weather Statement and/or Special Weather Statement (MWS or SPS) can be issued along the lines of the following example.

...CONDITIONS ARE FAVORABLE FOR WATERSPOUT FORMATION OVER THE BANANA RIVER BETWEEN PORT CANAVERAL AND THE MERRITT ISLAND CAUSEWAY...

AT 100 PM...NATIONAL WEATHER SERVICE RADAR INDICATED A RAPIDLY DEVELOPING LINE OF SHOWERS OVER THE BANANA RIVER 1 MILE WEST OF THE PORT CANAVERAL LOCKS. THESE SHOWERS WERE BUILDING SOUTH TOWARD THE MERRITT ISLAND CAUSEWAY ALONG THE SEABREEZE FRONT. SHOWERS DEVELOPING IN THIS AREA UNDER SIMILAR CONDITIONS HAVE OFTEN PRODUCED FUNNEL CLOUDS OR WATERSPOUTS. MARINERS AND COASTAL RESIDENTS ARE ADVISED TO MAINTAIN A CLOSE WATCH FOR FUNNEL CLOUD AND WATERSPOUT FORMATION IN THIS AREA AND MONITOR THIS DEVELOPING WEATHER SITUATION OVER THE NEXT FEW HOURS.

IF YOU SIGHT A FUNNEL CLOUD OR WATERSPOUT NEARBY...SEEK SAFE HARBOR AND SHELTER IN A REINFORCED BUILDING...AND REPORT THE SIGHTING TO THE NATIONAL WEATHER SERVICE...U.S. COAST GUARD...OR TO YOUR LOCAL LAW ENFORCEMENT OFFICIALS.

Purposes of this statement are to:

1) Heighten awareness of potentially severe weather, since effective advanced warning of the actual condition (spout) is often not possible.

2) Reduce the time needed for response, should a warning become necessary.

3) Provide mariners, especially those is slow vessels, enough time to avoid an area of potential development.

4) Encourage timely reports from the public, should an event occur.

Issuing such a statement does not eliminate the necessity for warning once an event occurs, but does offer an opportunity to heighten awareness and prepare the public for a possible event. It is also important to note that there will be more potential situations than actual events, so great care must be taken not to overuse such statements and risk reducing their effectiveness.

Although this statement has been tailored to WSO Melbourne, it is hoped that as future WSR-88D sites become operational along the southern United States coastline, additional offices will experiment with statements such as this to forewarn the public of potentially hazardous spouts.

7. Conclusion

The WSR-88D now provides the forecaster with the added capability of detecting radial wind velocities, in addition to reflectivity and other useful products. There are still limitations to this new technology; and recognizing these limitations will allow for better use of these products in forecasts and warnings.

In the WSO Melbourne coastal warning area, most of the past waterspout and coastal landspout formation has been isolated to a small area just west and south of Cape Canaveral. The warm, shallow and relatively large intracoastal lagoons and shape of the coast tend to localize convergence in this area. This produces a favorable location for thunderstorm initiation. On occasion, low level boundaries propagating through this area interact with rapidly developing cells to produce spouts. Due to the weak radar signatures and short-lived nature of such events, they have generally been warned for only after being sighted and often enough even after they have dissipated.

The spouts presented in this paper can be categorized into two groups - the stronger and longer lasting ones which form along boundary intersections indicative of the Cape Canaveral and Banana River cases. It is important to note that strong (F2+) spouts have formed with mesocyclone producing storms (Golden and Sabones 1991), but these are rare and are not addressed in this paper.

While it is well known that mesocyclones associated with supercells can be detected at great distances from a WSR-88D, any circulations associated with spouts often remain undetected since rotational signatures occur at lower levels, are much weaker, and are smaller in horizontal/vertical scale. Detailed post-analyses of seven recent spout events within 30 nm (56 km) of the Melbourne WSR-88D indicate only a hint of weak rotation in two of the cases. This rotation was only noticed in the 0.54 nm (1 km) resolution (best resolution on RPS list at the time) 1.5 degree elevation V and SRM products, and only for a few volume scans during the actual event.

Velocity signatures were only indicated with a few pixels and were embedded within an area of random inbound/outbound velocities, making real-time detection very difficult, and warning nearly impossible if based on velocity signatures alone. Even with the use of higher resolution velocity products, detection of low level circulations may prove difficult, since rotational velocity signatures of spouts typically are too small for the radar to decipher.

Detecting boundaries however, is a more common and easier task for the forecaster. Close monitoring of boundaries and anticipating the intersection or interaction among boundaries and rapidly developing cells near coastal regions is essential in identifying areas where spouts are likely to form. In addition, rapid, but subtle,increases in cell ET, VIL and CR often occur prior to the development of spouts. These two factors in combination with knowledge of local climatology have allowed forecasters at Melbourne to successfully provide information to the public about potential waterspout formation.

In this paper we have presented seven case studies which identify synoptic and mesoscale conditions favorable for coastal spout development. By combining local spout climatology studies with the knowledge of coastal geography and basic meteorological principles, the meteorologist using the WSR-88D may be able to provide coastal residents and mariners with additional lead-time concerning potentially dangerous spout events. To heighten public awareness for the potential of spout formation, a Marine Weather Statement or Special Weather Statement can be issued for a portion of the coastline. We have provided an example of such a statement which has been used at Melbourne and may be applicable at other locations.

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